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Fertilizer and Pesticide Movement from Citrus Groves in Florida Flatwood Soils

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16. ABSTRACT

Concentrations and discharge amounts of NO_3-N, PO_4-P, 2,4-D herbicide, terbacil herbicide, and chlorobenzilate acaricide were determined in surface and subsurface drainage waters from a citrus grove located in an acid, sandy flatwood soil of southern Florida. The influence of fertilizer and pesticide upon water quality was examined for citrus growing in three soil management treatments: ST (shallow-tilled plowed to 15 cm); DT (deep-tilled and soil mixed within the top 105 cm); and DTL (deep-tilled to 105 cm and 56 Mt/ha of dolomitic limestone mixed with the soil).

Average annual losses of NO_3-N in both surface and subsurface drainage from ST, DT, and DTL plots were equivalent to 22.1, 3.1, and 5.4% of total N applied as fertilizer. Average annual losses of PO_4-P in both surface and subsurface drainage from ST, ST, and DTL plots were equivalent to 16.9, 3.6, and 3.5% of total P applied as fertilizer. Deep tillage was thus observed to greatly decrease leaching loss of N and P nutrients. Loss of nutrients in surface runoff was very small for all three plots. Although the magnitudes were less, deep tillage also decreased leaching losses of terbacil and 2,4-D herbicide. Discharges of these herbicides in subsurface drainage were usually in the order: ST>DTL>DT. Discharge of 2,4-D was greater from drains with open outlets than from drains with submerged outlets. Discharge of terbacil did not differ for open or submerged drains. Chlorobenzilate pesticide was not detected in drainage water from either of the three soil treatments.

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FERTILIZER AND PESTICIDE MOVEMENT FROM CITRUS GROVES IN FLORIDA FLATWOOD SOILS

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FOREWORD

Environmental protection efforts are increasingly directed towards preventing adverse health and ecological effects associated with specific compounds of natural or human origin. As part of this Laboratory's research on the occurrence, movement, transformation, impact, and control of environmental contaminants, the Technology Development and Applications Branch develops management or engineering tools for assessing and controlling adverse environmental effects of non-irrigated agriculture and silviculture.

This study was conducted to investigate the influence of applied fertilizers and pesticides upon the water quality of surface and subsurface drainage. Various soil management practices, particularly tillage systems, were evaluated as controls for losses of fertilizer and pesticide from the rapidly expanding citrus groves of southern Florida. If guidelines furnished here are followed, citrus grove managers can make more efficient, cost-effective use of fertilizers and herbicides and, at the same time, reduce the contribution of this non-point source of pollution to our waterways.

David W. Duttweiler
Director
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Athens, Georgia

ABSTRACT

Concentrations and discharge amounts of NO_3-N, PO_4-P, 2,4-D herbicide, terbacil herbicide, and chlorobenzilate acaricide were determined in surface and subsurface drainage waters from a citrus grove located in an acid, sandy flatwood soil of southern Florida. The citrus grove received routine applications of fertilizer, pesticide, and irrigation water as needed. The grove was established in 1970 by placing trees in two rows on top of soil beds which were separated by furrows for surface runoff. Subsurface plastic drain tubes placed at 107 cm depth and spaced 18.3 m apart were installed perpendicular to the soil beds.

The influence of fertilizer and pesticide upon water quality was examined for citrus growing in three soil management treatments: ST, DT, and DTL. The ST or shallow-tilled plot was plowed to 15 cm depth, the DT or deep-tilled plot was established by mixing the top 105 cm of the soil profile with a trenching machine, and the DTL plot was also deep tilled to a depth of 105 cm with 56 mt/ha of dolomitic limestone mixed with the soil. A drained untilled, unfertilized control plot without citrus was also established.

Following an individual rainfall or irrigation event, water flux from subsurface drains as well as drawdown of the water table at the midplane between parallel drains were consistently greater from the shallow-tilled plot relative to the deep-tilled plots. However, drainage from DT was more rapid than from DTL. Average annual quantities of drainage from ST was equivalent to 50% of total rainfall plus irrigation. For DT and DTL plots drainage water represented only 28 and 17%, respectively, of total water input.

Routine applications of fertilizer increased concentrations of NO_3-N and PO_4-P in drainage water from all three plots. Greatest leaching losses of these nutrients occurred from ST. Average annual losses of NO_3-N in both surface and subsurface drainage from ST, DT, and DTL plots were equivalent to 22.1, 3.1, and 5.4% of total N applied as fertilizer. Average annual losses of PO_4-P in both surface and subsurface drainage from ST, DT, and DTL plots were equivalent to 16.9, 3.6, and 3.5% of total P applied as fertilizer. Deep tillage was thus observed to greatly decrease leaching loss of N and P nutrients. Loss of nutrients in surface runoff was very small for all three plots.

Although the magnitudes were less, deep tillage also decreased leaching losses of terbacil and 2,4-D herbicide. Discharges of these herbicides in subsurface drainage were usually in the order: ST > DTL > DT. Discharge of 2,4-D was greater from drains with open outlets than from drains with submerged outlets. Better aeration in soil surrounding open drains was believed to have enhanced microbiological degradation of 2,4-D. Discharge of terbacil, which has a tenfold greater half-life than 2,4-D, did not differ for open and submerged drains. Chlorobenzilate pesticide was not detected in drainage water from any of the three soil treatments.

This report was submitted in fulfillment of Grant No. R-800517 by the Institute of Food and Agricultural Sciences of the University of Florida under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from May 1, 1973 to December 31, 1976, and work was completed as of April 1, 1977.

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SECTION I

INTRODUCTION

During the past 50 years, improved soil water management and increased utilization of fertilizers and pesticides have contributed greatly to increased production of agricultural crops. Increased crop yields per unit land area are largely responsible for the relatively low costs for food and fiber commodities currently available to the American consumer. Agricultural scientists are therefore presently concerned with the development of water and chemical management of crops which will improve production efficiency for consumer commodities and simultaneously prevent the contamination of the soil-water environment with undesirable concentrations of chemicals from applied fertilizers and pesticides. Thus the objectives for agricultural research are multifold: to prevent pollution of groundwater and other water supplies, to prevent eutrophication of lakes, to provide efficient utilization of irrigation water and costly fertilizer nutrients by crops, and to provide effective control of weed, insect and microbiological pests.

The occurrence of potentially harmful concentrations of agrichemicals in groundwater, drainage canals, and streams may be greatest (Nelson, 1972) in areas where cash crops are grown mainly on sandy soils which receive frequent applications of irrigation water, insecticide, herbicide and fertilizer. Such conditions exist in the humid, subtropical climate of Florida. Recent investigations indicate that under certain crop management practices the possibility exists for substantial leaching losses of fertilizer nutrients in acid, sandy soils of Florida (Calvert and Phung, 1971; Calvert, 1975; Forbes *et al*., 1974; and Graetz *et al*., 1974). However, the exact fate of applied fertilizer materials was not shown in these studies. Soil management practices are needed for crops growing in a humid climate on sandy soils to prevent or minimize pollution resulting from discharge of agricultural chemicals through surface and subsurface drainage waters. Basic information, however, is lacking for concentrations as well as discharge of nutrients and pesticides in drainage water from individual agricultural fields, and how the loss of these chemicals is affected by management of soil, water, fertilizer, and pesticide resources.

A brief search of the literature readily shows that many factors affect the loss of pesticides or nutrients such as nitrogen and phosphorus in surface runoff and drainage waters from subsurface-drained agricultural soils. Jury (1975) stated that "The solute flux or concentration of water collected at the tile contains contributions from all parts of the field being drained, in proportions which depend on tile line spacing, soil permeability variations, and type of infiltration (ponded or unsaturated). This complex superposition, coupled with a phase delay due to travel time variations from point to point on the field, greatly obscures the relationship between input and output".

Although soil water is the medium by which solutes such as nitrate are transported through soil, water and dissolved chemicals do not always move with the same velocity. Biggar and Corey (1969) state that the movement of solutes through soil frequently lags behind water movement largely due to mixing processes such as diffusion and hydrodynamic dispersion which occurs between the resident soil solution and infiltrating water from irrigation or rainfall. In addition, ions such as ammonium or phosphate can be further detained in their movement in the direction of soil water flow by adsorption-desorption interaction with soil colloids. Phosphorus in the soil solution can also undergo precipitation with iron and aluminum and therefore be removed from the solution phase. Ammonia, of course, is also subject to microbiological transformations to form nitrate under aerobic soil conditions, and nitrate is subject to form N_2O and N_2 gases under anaerobic conditions. Soluble organic herbicides such as terbacil and 2,4-D also move through soil at velocities considerably less than that for water. These herbicides are subject to adsorption-desorption and microbiological degradation, as well as many other processes. In general adsorption has been shown to be a better indicator of potential movement in soil than solubility in water (Biggar, 1970). Thus, change in concentrations of fertilizer nutrients and pesticides in surface runoff and drainage waters is a complex function of time due to solute dispersion, transport, interactions with the soil, and microbiological transformations.

The quantity and velocity of water flowing through soils to subsurface drains are of major importance to the leaching loss of applied fertilizers and herbicides. Bolton et al. (1970) measured nutrient losses in tile drainage water for crops growing on a clay soil for a 7-year period. They concluded that the total volume of drainage water for a particular cropping system was the predominant factor influencing nutrient loss. Discharge of nutrients was distinctly greatest during seasons when large amounts of drain flow occurred. Water uptake by plants (transpiration) tends to decrease the volume of drainage from the soil. Both Bolton et al. (1970) and Erickson and Ellis (1971) observed less fluctuation in concentration of a given nutrient in drainage water with time during a specific season than for the fluctuations of discharge flux (product of solute concentration and drainage water flux) for the nutrient.

Removal of fertilizer nutrients from the mobile soil solution by growing plants is generally considered to be relatively inefficient. Ayers and Branson (1973) state that uptake of applied nitrogen is frequently 50% or less. Recovery of applied phosphate by plants averages about 30% (Nelson, 1975). A large portion of the nitrogen that is not removed by crops is subject to potential leaching loss from the root zone. Johnson et al. (1965) found that rather large percentages of applied nitrogen (range: 9-70%) were lost in tile drainage effluent from irrigated land in California. Losses of phosphorus were much less (range: 1-17%).

Frink (1971) states that the efficiency of nitrogen uptake by a crop is greatly influenced by the rate, the method, and the timing of fertilizer applications. Of these three factors, proper timing of fertilization appears the most important. He states that by timing applications of fertilizer to coincide with maximum demand of the crop, less nitrogen is required to produce the same crop yield.

Generally speaking, concentrations of NO_3-N are lower in surface runoff water than in subsurface drainage; whereas, the concentration of soluble P is usually higher in runoff water than in drainage (Biggar and Corey, 1969). The concentration of soluble P is frequently less than 0.01 μg/ml in the soil solution of the subsoil horizons of most soils (Biggar and Corey, 1969). Thus the concentrations of P in subsurface drainage water is normally very low. However, Bingham et al. (1971) measured NO_3-N concentrations as high as 20 μg/ml in subsurface drainage water from a large citrus watershed in California.

Ayers and Branson (1973) observed that nitrate concentrations tend to be higher in groundwater located beneath sandy soils which are intensely managed for agricultural use. Also concentrations of NO_3-N in soil solution samples taken from the root zone of soil beneath a citrus grove increased from 19.3 μg/ml for low nitrogen fertilization (150 lbs. N/acre/yr.) to 45.5 μg/ml for high nitrogen fertilization (350 lbs. N/acre/yr.).

During 1968 an interdisciplinary research team comprised of scientists employed by the University of Florida and the Agricultural Research Service of the U. S. Department of Agriculture was assembled under the Soil-Water-Atmosphere-Plant (SWAP) Project (Knipling and Hammond, 1971). The SWAP project was established fo the purpose of developing a research program to solve pertinent problems associated with soil, water, atmosphere and plant resources for agricultural production. A field experiment was established on a 20-hectare area at the Agricultural Research Center, Fort Pierce, Florida to evaluate the effects of three soil management systems - Shallow Tillage (ST), Deep Tillage (DT), and Deep Tillage Plus Lime (DTL) - and two drainage systems - subsurface drains with Submerged (S) and Open (O) outlets - on soil and water properties, drainage characteristics of the soil, and growth response of 12 citrus rootstock/scion combinations. Historical background of the project and a detailed description of the design and objectives of the SWAP study have been given by Knipling and Hammond (1971). Soil within the experimental area are classified as Spodosols (acid flatwood soils) which represent a major physiographic unit within Florida (Figure 1) and in the Southeastern United States. The land area shown in Fig. 1 and designated as Spodosols also includes the order of Alfisols which are sandy soils with larger contents of colloidal material (clay minerals and organic matter) than the associated Spodosols. This schematic map provides only a very general description of the location of large areas of Spodosols in Florida. Compared to the Spodosols, the Alfisols are generally more fertile soils.

Spodosols and other associated flatwood soils represent the most extensive order (Zelazny and Carlisle, 1971) of Florida soils and account for approximately 25% of the total land area. Sites et al. (1964) have stated that approximately 5 million acres of flatwoods and marshes occur just in the central and southern sectors of the state. Generally, Spodosols occur on nearly level to gently sloping landscapes with a shallow groundwater table which fluctuates near the soil surface during summer and early fall periods of high rainfall (Brasfield et al. 1973). Spodosol profiles are characterized by the presence of a subsurface spodic horizon which is an accumulation of organic matter with varying amounts of aluminum and iron. The spodic horizon usually (Brasfield et al. 1973) has relatively high levels of cation exchange capacity, specific surface area, water retention capacity, and exchangeable acidity. This horizon commonly occurs at depths less than 75 cm beneath the soil surface and is overlain by sandy A_2 eluvial and A_1 surface horizons. Spodosols are typically strongly acid sandy soils which have low levels of fertility and base saturation. Internal drainage of these soils is generally limited by the presence of the spodic horizon which is slowly permeable to water. However, if parallel subsurface drains are placed in these soils, lateral drainage through the A_2 horizon can be rapid, particularly where the spacing between drains is small.

During 1973 the Environmental Protection Agency funded Grant #R800517 to investigate the influence of applied fertilizers and pesticides upon the water quality of surface runoff and subsurface drainage waters in the SWAP citrus grove. The objectives of that project were as follows: (1) to determine the movement and fate of NO_3-N, PO_4-P, terbacil, 2,4-dichlorophenoxyacetic acid, and chlorobenzilate through the soil profile and into drainage water from a citrus grove, (2) to evaluate the influence of the three soil management systems - Shallow Tillage (ST), Deep Tillage (DT) and Deep Tillage plus Lime (DTL) - and the two drainage systems - Submerged (S) and Open (O) drain outlets - upon the concentration and flux of selected agrichemicals in surface runoff and subsurface drainage waters, and (3) to determine base-level concentrations of selected agrichemicals in subsurface drained soil which has sod vegetation and that has received no applications of fertilizer and pesticides.

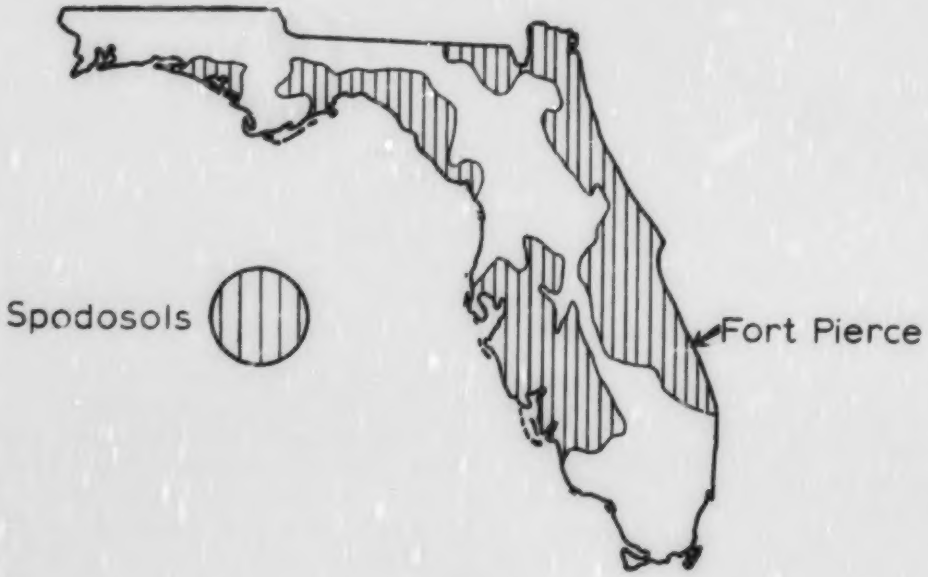


FIGURE 1. Map of Florida showing locations of major areas of Spodosols.

SECTION II

CONCLUSIONS

Acid, sandy Spodosol soils of Florida are typically poorly drained. The presence of subsurface spodic and clay strata in the profile impede water flow vertically from the profile and enhance lateral flow along the top of the spodic layer. Nearly flat topography also limits rates of surface and lateral subsurface drainage. During periods (summer) of frequent rainfall a water table develops in the soil profile and sometimes inundates the soil surface. Agricultural development of flatwood land thus normally includes establishment of ditch or subsurface drainage systems for the purpose of removing excess soil water and maintaining a water-unsaturated root zone in the upper portion of the soil profile for optimum plant growth. Citrus trees are grown on these soils using slightly elevated beds to provide surface drainage and either open ditches or buried tiles to provide subsurface drainage.

Both the nutrient and water retention capacities for the sandy surface horizons of Spodosols are characteristically small. Consequently, agricultural management of citrus growing on flatwood soils usually includes quarterly applications of fertilizer and applications of irrigation water as needed during periods (winter and spring) of infrequent rainfall. In addition to fertilizer, other chemicals such as herbicides, insecticides, fungicides, and acaricides are applied to control specific pests.

Agricultural chemicals such as fertilizers and pesticides applied to citrus groves on drained flatwood soils are occasionally suspect as potential contaminants of groundwater and drainage canals. Primary objectives for this research project were first to quantitatively assess the water pollution potential of two fertilizers--nitrogen and phosphorus--and three pesticides--terbacil, 2,4-D, and chlorobenzilate--when applied during routine management of a subsurface-drained citrus grove located on a Spodosol and second to evaluate the influence of three soil management schemes--shallow tillage (ST), deep tillage (DT), and deep tillage plus lime (DTL)--upon the water pollution potential of these chemicals. An unfertilized Control plot with subsurface drainage but without citrus trees was also established. Volumetric discharge rates and chemical analyses of surface runoff and subsurface-drainage waters were measured with time. Water flux and chemical concentrations were integrated to determine discharge of the 5 applied agricultural chemicals with surface and subsurface drainage.

Based upon results obtained from this research, the following conclusions were made:

(1) Following periods of rainfall or irrigation, flux and accumulative discharge of subsurface drainage were consistently greater from the shallow-tilled treatment, ST, relative to that for the deep-tilled treatments, DT

and DTL. Drainage flux and accumulative discharge from the soil management treatments were in the order: ST >> DT > DTL ≈ Control. Average monthly amounts of drainage from ST were approximately twice that for DT.

Average annual quantities of subsurface drainage for the three-year period 1973-75 were 78, 43, and 27 cm, respectively for ST, DT, and DTL plots. The average annual sum of rainfall and irrigation for the same period was 155 cm. Thus drainage water from the ST plot was equivalent to 50% of the total water input from rainfall and irrigation. For DT and DTL plots drainage water represented only 28 and 17%, respectively of total water input. This observation indicates that the slower drainage in the deep tilled treatments provided opportunity for storage of infiltrated water over longer periods of time than for the shallow-tilled plot. Thus deep tillage tended to increase the length of time for water storage in the soil profile following rainfall or irrigation. In fact estimated values of evapotranspiration for the three treatments were in the order ST << DT < DTL.

Drawdown of the water table in the soil at the midplane between parallel subsurface drains was in the order ST >> DT > DTL. During a ten-day period following an irrigation of 16 cm of water, approximately 1.4, 3.0, and 6.2 days were required for the water table to move from near the soil surface to a depth of 60 cm for ST, DT, and DTL plots. Although the very rapid drawdown of the water table in the ST plot provides for rapid establishment of aeration in the rooting zone, the accompanying rapid movement of soil water also increases the potential for greater loss of applied fertilizer nutrients.

Overall growth of citrus trees and fruit yields for the three treatments were in the order ST << DT ≤ DTL and ST ≈ DT << DTL, respectively. The deep tillage treatment thus improved growth and yields from citrus, probably due to increased capacities for temporary storage of water and nutrients in the root zone of the soil profile.

(2) Greatest leaching losses with subsurface drainage from the soil profile for both NO_3-N and PO_4-P occurred from the ST treatment. Concentrations of PO_4-P appearing in the drainage water from the ST plot were higher than expected. Both DT and DTL plots leached very small amounts of PO_4-P compared to that for an unfertilized Control plot apparently due to the greater surface area and chemical nature for retention of PO_4-P provided by the colloidal organic and inorganic materials which were incorporated into the otherwise sandy profile by the deep tillage. The DTL treatment gave significantly more NO_3-N discharge into the drains than the DT treatment and was probably due to the higher nitrification rate found for the DTL soil.

Average annual losses of NO_3-N in surface and subsurface drainage from ST, DT, and DTL plots were equivalent to 22.2, 3.1, and 5.4% of total N applied as fertilizer. Thus deep tillage decreased NO_3-N loss by approximately fourfold over shallow tillage. Loss of NO_3-N from the combined treatments of deep tillage plus lime was also greater than for the single treatment of deep tillage.

Average annual losses of PO_4-P in surface and subsurface drainage from

ST, DT, and DTL plots were equivalent to 16.9, 3.6, and 3.5% of total P applied as fertilizer. Thus deep tillage decreased P loss by more than fourfold over shallow tillage. Essentially no differences were observed in P loss from DT and DTL plots. Annual losses of both N and P were relatively high for the ST plot.

The ratios of NO_3-N and P discharged in subsurface drainage from all three soil plots were greater than the ratio of 9.2 for N and P applied as fertilizer. For ST and DT the N-to-P ratios were 12.1 and 10.5, respectively. However, the N-to-P ratio in drainage from DTL was 20.3 or almost twice that for either ST or DT. The large N-to-P ratio for DTL reflects the smaller leaching loss of P and the larger leaching loss of N relative to that for DT. For the nutrient content of oranges the average ratio of N-to-P is 8.0 which is slightly less than the ratio of 9.2 for the fertilizer.

(3) Timing of fertilization with respect to rainfall or irrigation events was observed to greatly influence leaching loss and thus nutrient enrichment of subsurface drainage water. Losses of NO_3-N in drainage from ST soil were relatively large and depended upon the quantity of water applied when irrigation immediately followed application of fertilizer. During 14-day periods following 16.0, 8.2, and 2.4 - cm irrigations NO_3-N losses represented 34, 13, and 2% of N applied in the fertilizer for ST. Discharges of NO_3-N from DT after 16.0, 8.2, and 2.4 - cm irrigations were only 1.34, 1.06, and 0.02%. However, comparable losses from DTL were 12, 8, and 0.2%, respectively. Losses of PO_4-P in drainage after the 16.0, 8.2, and 2.4 - cm irrigations were 8, 3, and 0.9% for ST; 1.56, 0.14, and <0.01% for DT; and 2.31, 0.12, and <0.01% for DTL.

(4) Potential leaching losses of applied N and P for citrus growing on tile-drained Spodosol was observed to be greatest during the six-month period from May through October. During these periods for 1973 - 1975 approximately 78% of annual rainfall occurred. During these high-rainfall months NO_3-N discharged with subsurface drainage accounted for 78% of the total annual loss of NO_3-N from ST, 83% for DT, and 74% for DTL. Losses of PO_4-P accounted for 90, 89, and 88%, respectively of total annual quantities discharged from ST, DT, and DTL.

(5) Application of fertilizer was observed to increase the concentrations of NO_3-N and PO_4-P in drainage water from ST, DT, and DTL plots. However, as the drainage water moved through a long perimeter ditch to the South Sump the concentrations of nutrients were greatly decreased. Nutrient concentrations in drainage water sampled from the surrounding perimeter ditch and from the non-tilled, unfertilized Control plot and in the South Sump for the entire SWAP citrus grove were generally much lower than that found in the drainage water from the tilled and cropped areas. The lower concentration of P in the ditch and South Sump can probably be explained by fixation of P with clay minerals in the ditch banks and by uptake by plants in and near the water. A dilution effect also was caused by water coming from unfertilized areas. NO_3-N probably was absorbed by plants and underwent denitrification in the anaerobic conditions of the ditch bottom.

(6) Losses of NO_3-N and PO_4-P with surface runoff were very small for all

treatments. Runoff rarely occurred from ST and occurred from the deep-tilled plots only during intense rainfall or irrigation of long duration. Runoff occurred after the soil profile had become water-saturated.

(7) Denitrificationcan be a significantly large sink for nitrogen applied as fertilizer to the DT and DTL treatments. The relatively slow drainage characteristics of these deep-tilled soils in conjunction with the capacity of the soil located in the lower portion of the profiles to denitrify nitrate-N contribute to this sink. In the ST or shallow-tilled soil denitrification takes place only in the surface or A_1 horizon. Since the soil in the A_1 horizon is seldom water-saturated under conditions of subsurface drainage, considerably less denitrification is likely to occur in the ST soil relative to that in the DT and DTL soils. Rate coefficients for denitrification were found to be (average for three soil depths) 2.24, 0.44, and 0.88 10^{-3}/hr for ST, DT, and DTL soil. Thus the DTL soil has a greater potential for denitrifying NO_3-N than does DT soil.

(8) Although deep tillage clearly decreased nutrient (mainly P) leaching losses from the soil its affect upon pesticide loss was not as dramatic. Discharge measurements in drainage indicated some movement of terbacil and 2,4-D herbicides but essentially nil loss of chlorobenzilate. The results with chlorobenzilate were expected since it is not a water-soluble material and it was applied directly to the citrus foliage. Losses of terbacil and 2,4-D in subsurface drainage of DT and DTL plots was, however, less than that for ST. Total discharges of these two herbicides were in the order ST > DTL > DT.

Discharge of herbicide with subsurface drainage was affected by the type of drain outlet. For 2,4-D, leaching loss was greater from drains with open outlets than from drains with submerged outlets. Loss of terbacil in drainage, however, was not greatly different for open and submerged drains. Since the half-life of 2,4-D is approximately one tenth of that for terbacil, the higher water content and poorer aeration in soil above submerged drains is believed to have influenced microbial degradation of 2,4-D more so than for terbacil.

(9) Changes in concentration of NO_3-N in subsurface drainage from DTL soil was observed to follow changes in concentration of soil solution surrounding the drain tube. However, NO_3-N concentrations in portions of the upper 60 cm of soil were as high as 120 μg/ml in the soil solution even when the concentration in drainage water was less than 8 μg/ml.

(10) A mathematical model was developed to describe the simultaneous transport of P and water through soil. Kinetic theory was used to incorporate reversible transformations of P between dissolved, adsorbed, immobilized, and precipitated phases.

SECTION III

RECOMMENDATIONS

I. The following management guidelines are recommended to citrus grove operators and other land management specialists for controlling pollution from non-point sources of fertilizer and pesticide in citrus groves located on Spodosols:

A. Excessive rates of fertilizer and herbicide application are wasteful and contribute to unnecessary pollution of our waterways. Rates and timing of chemical applications should coincide with citrus demand for nutrients and should be consistent with soil water management (irrigation, rainfall, drainage, etc.). Fertilizer applications should be minimized during Florida's summer rainy season to avoid excessive leaching of nutrients from fertilized soil. Most efficient usage or uptake by plant roots of applied fertilizer occurs when the use-efficiency of infiltrated rainfall and irrigation is also large.

B. Although expensive, deep-tillage appears to be a practical management method for flatwood soils (Spodosols). If horizons of fine textured material exists in the subsoil, colloidal materials can be incorporated into the otherwise coarse sandy surface soil and thereby reduce leaching of applied agrichemicals.

C. Collecting the drainage water from citrus groves in reservoirs for recycling through irrigation systems could permit recovery of some of the discharged nutrients and increase the water use-efficiency during periods of limited rainfall.

D. Although the deep tillage treatment was observed to decrease leaching losses of applied nutrients and herbicides, initial costs for establishment of deep tillage by the trenching method is currently about $18,664 per hectare which is prohibitive for use by commercial citrus growers. Several options are available however for utilizing the deep tillage treatment at much less cost.

One alternative is to use the trenching method to deep-till a 45-cm swath along the rows of citrus trees. Estimated cost for selective deep tillage would be only $1,023 per hectare. Growing citrus trees under those conditions would be somewhat like growing the trees in large pots since leaching loss of nutrients and water could be greatly decreased in the deep-tilled soil adjacent to the tree rows. Applications of fertilizer would be restricted to the surface soil of the deep-tilled swath. More efficient water use could also be provided by applying irrigation water directly to the base of the trees using the drip/trickle method.

Shallow placement of smaller drains with narrower spacing could also be used as an alternative to the deep placement of large drains with wide spacing as currently used at the SWAP citrus grove. Recent work by Fausey (1975) indicates that shallow subsurface drains can be used to control seasonal high water tables in soils with an impermeable or slowly permeable layer at a shallow depth. Relatively small diameter corrugated plastic draintubes can be installed at shallow depths (Fausey, 1975) by the "plow-in" method for considerable cost savings over conventional trenching methods for installing deep drains. Fausey (1975) used a finite difference model to simulate transient water flow to drains in a two-layer soil where the depth to the impermeable lower boundary was 150 cm and the layer interface was 55 cm from the ground surface. He concluded that if the hydraulic conductivity for soil in the top layer was 5 times or more greater than that for the bottom layer, the rate of midplane recession of the water table during early stages of drawdown was greatest when the drain was placed at 50 cm depth. Fausey (1975) concluded that shallow drainage of layered soils appears to be feasible.

Another alternative means for establishing deep tillage over the entire soil area at a greatly reduced cost over the trenching method is to use a moldboard plow. Kaddah (1976) stated that deep tillage of a soil profile could be accomplished to a depth of 120 cm by moldboard plowing for a cost of $148-198 per hectare. The cost is further increased, however, by cost for land leveling which is required after deep moldboard plowing.

Estimated current costs for initial establishment of a pop-up sprinkler irrigation system and subsurface plastic drain tubes are $2,471 and $2,242 per hectare, respectively for either shallow-tilled or deep-tilled plots.

2. The following future research studies are suggested for providing additional insight into the effects of routine applications of fertilizer and herbicide upon the quality of groundwater and water in canals:

   A. To assess the amount of nutrient and pesticide movement under the common (in Florida) grove drainage situation of surface and subsurface drainage by widely spaced ditches, samples should be collected during peak periods from ground water draining from groves planted on Spodosols and otherwise developed similarly to ST treatment except with ditch spacing greater than the relatively narrower drain spacing used in this study.

   B. The effectiveness of removing nutrients and pesticides from drainage water by storage and recycling from reservoirs should be assessed in a study conducted at the SWAP citrus grove.

   C. To more precisely identify the source of nitrates found in the drainage water and determine paths for movement of N in subsurface-drained soil a study, using $^{15}NO_3$-N or similar tracer should be conducted.

D. Maximum discharges of nutrients and pesticides should continue to be determined on a long-term basis, particularly for years when the total rainfall exceeds the average. In the present long-term study the total rainfall amounts were average or below.

E. To make best use of current data presented in this report, a mathematical model should be developed to simulate two-dimensional transport of water and agrichemicals (NO_3-N, NH_4-N, P, K, and terbacil) during non-steady water infiltration and drainage of a fertilized Spodosol resulting from irrigation or rainfall events. Such a model should also describe interactions such as adsorption-desorption, chemical precipitation, fixation, denitrification, and nitrification. Experimental measurements of water content and solute concentration in soil surrounding a subsurface drain are also needed to validate results from such a model. Concentrations of agrichemicals in the drainage water should be compared with concentration distributions in the soil solution.

SECTION IV

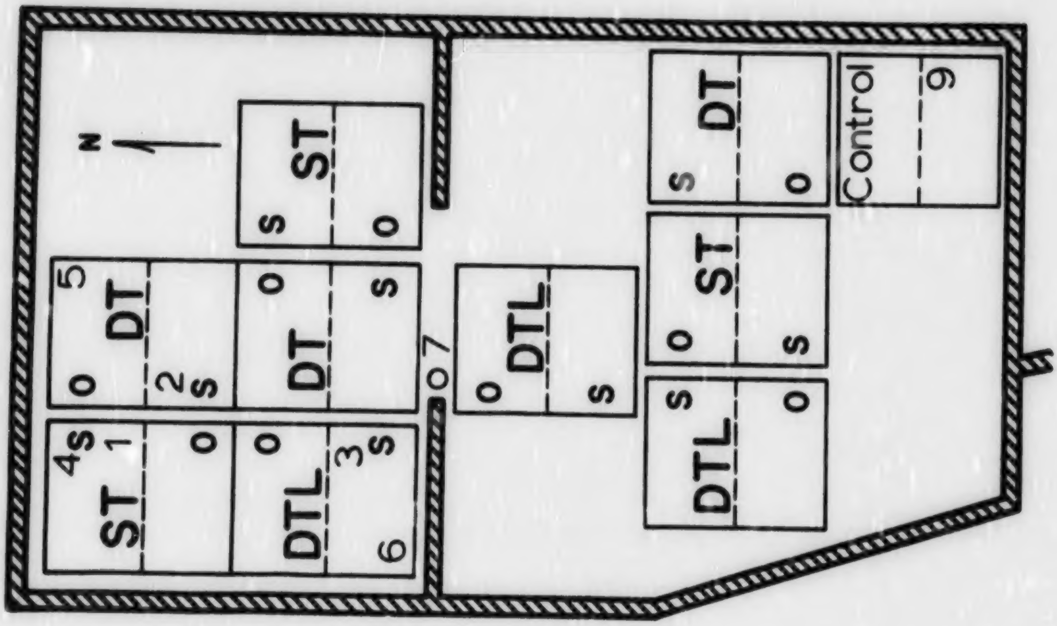
CONCENTRATION AND FLUX OF NO_3-N AND PO_4-P IN SURFACE AND SUBSURFACE DRAINAGE WATER FROM A FERTILIZED CITRUS GROVE

EXPERIMENTAL METHODS AND PROCEDURE

Field Procedures

A schematic diagram of the entire SWAP experimental field site is shown in Figure 2. A single replicate each of the ST, DT, and DTL soil management treatments were selected from the northwest corner of the site for the purposes of performing research on EPA Grant #R800517. The primary soil type in the selected area of study was Oldsmar sand, a member of the sandy siliceous, hyperthermic family of Alfic Arsenic Haplaquods (Spodosol). The dark spodic horizon ranged in depth from 86 to 107 cm with an average of 96 cm in undisturbed profiles; this spodic horizon (many Spodosols do not have such sandy clay material beneath the spodic horizon) was underlain by layers of fine sandy clay. The A_1, A_2, and A_{22} horizons of acid sand had a total average depth of 82 cm and the organic content was 2.30% in the surface A_1-horizon soil (Table 1) but decreased with depth. These sandy horizons are highly permeable to water flow and are underlain by 10 to 20 cm of a nearly impermeable (saturated hydraulic conductivity of 0.02 cm/hr) spodic layer containing 3.56 percent organic matter (Table 1). The spodic layer is underlain mostly by sandy clay loam which like the spodic layer has a low saturated hydraulic conductivity (0.12 cm/hr) and is thus also slowly permeable to water flow.

Main plot treatments in the entire SWAP field experiment consisted of three profile modifications. Each plot (Fig. 3) contained 3 open-outlet drains and 3 submerged-outlet drains and was approximately 1 ha in area (91.4 by 109.7 m). Treatments were replicated three times. Soil modification treatments were as follows: (i) Shallow-Tilled (ST) to 15 cm depth and normal surface liming with dolomitic limestone (2.24 metric tons ha^{-1} $year^{-1}$); (ii) Deep-Tilled (DT) to 105 cm depth by a trenching machine and with the same liming as the ST treatment; and (iii) an initial application of 56 metric tons ha^{-1} dolomitic limestone subsequently incorporated by deep-tillage (DTL) of the soil to a depth of 105 cm. All of the limestone contained approximately 60% agricultural grade dolomite (40% coarse grade dolomite). Surface drainage was provided in ST, DT, and DTL plots by establishing 38 cm (height of bed crown above bottom of water furrow) high and 15.2 m wide (measured from centers of water furrows) beds sparated by parallel water furrows. Swale ditches established at each end of the water furrows and perpendicular to the furrows provided removal of surface drainage water from the experimental plots. Two citrus rows 7.6 cm apart and with a spacing of 4.6 m between trees in each row were established along the top of each bed. Subsurface drainage was provided by 10-cm corrugated plastic tubing placed at an average depth of 107 cm and spaced 18.3 m apart. Surface drainage by



Sampling Sites

1. Surface tilled submerged drain
2. Deep tilled submerged drain
3. Deep tilled limed submerged drain
4. Surface tilled surface runoff
5. Deep tilled surface runoff
6. Deep tilled limed surface runoff
7. Center Sump
8. South Sump
9. Control drain

FIGURE 2. Schematic diagram of the SWAP field experiment located at the Agricultural Research Center, Florida Agricultural Experiment Station, Fort Pierce, Florida. Locations for nine sampling sites are shown.

Table 1. Selected physical and chemical properties of representative profile horizons sampled from Oldsmar sand at the SWAP citrus grove near Fort Pierce, Florida.

Soil Profile	Horizon	Depth	Sand	Silt	Clay	Organic Matter[2]	Cation Exchange Capacity[2]	Bulk Density	Hydraulic Conductivity[1]	Volumetric H_2O Content at Saturation[1]
		(cm)	---------	%	---------	(%)	(me/100g)	(gm/cm³)	(cm/hr)	(vol. %)
ST	A_1	2-8	96.2	2.6	1.2	2.30	1.03	1.28	29.5	44.8
ST	A_{21}	18-23	98.3	0.7	1.0	0.62	0.70	1.55	26.3	34.3
ST	A_{22}	50-56	97.9	1.0	1.1	0.09	0.49	1.64	27.4	29.4
ST	B_{2h}	86-91	88.6	3.3	8.1	3.56	1.18	1.75	0.02	31.5
ST	B_{21}	107-112	88.1	0.4	11.5	0.26	4.25	1.62	10.9	31.6
ST	B_{22tg}	130-135	76.1	1.0	22.9	0.18	4.32	1.68	1.6	36.6
ST	B_{23tg}	188-194	----	---	----	----	----	1.78	0.12	33.4
DT	Mixed	0-50	----	---	4-6[2]	1.21	1.57	1.61	8.9	34.0
DTL	Mixed	0-50	----	---	4-6[2]	1.21	3.32	1.61	8.9	34.0

[1] Data from Hammond, Carlisle and Rogers (1971).

[2] Data from Fiskell and Calvert (1975).

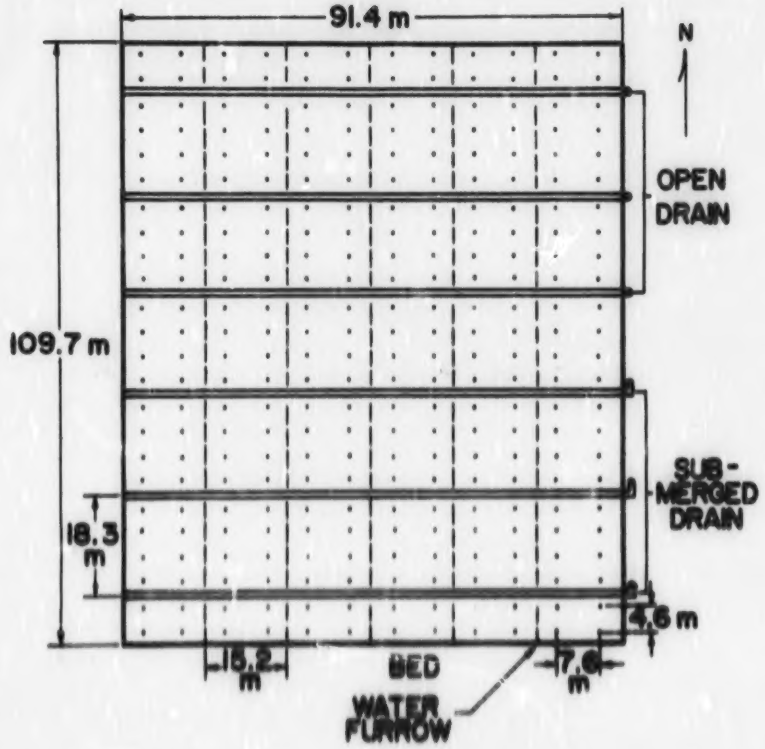

91.4 m
N
OPEN
DRAIN
109.7 m
SUB-
MERGED
DRAIN
18.3
m
4.6 m
15.2
m
BED
7.6
m
WATER
FURROW

FIGURE 3. Schematic diagram of a single main plot showing split plots (submerged and open drains). Dots indicate the location of citrus trees on beds.

raised, multiple-row beds and subsurface drainage by either tile drains or open ditches are commonly recommended (Sites et al., 1964) for citrus growing on flatwood and marsh soils of Florida. In general the water table in such soils should not be allowed to rise closer than 60 cm from the soil surface.

In the DT and DTL treatments deep tillage removed soil material high in colloidal (clay minerals and organic matter) content from the subsurface spodic (B_{2h}) and sandy clay horizons (B_{21} and B_{22tg}) and mixed this material with the sandy A_1, A_{21}, and A_{22} horizons. Thus the DT and DTL soil profiles contained higher contents of clay minerals and organic matter (Table 1) in the top 50 cm than were present in the same depths of the ST soil profile. In the surface soil the cation exchange capacity (Table 1) was higher for DT (1.57 me/100g) than for ST (1.03 me/100g) and approximately twice as high in DTL (3.32 me/100g) than in DT.

Three plots in the northwest corner of the SWAP citrus grove which represent each of the three soil treatments were chosen (Figure 2) as sites for monitoring the water quality of surface and subsurface drainage waters. Only the center drains with submerged outlets for each plot were monitored. Water from both surface runoff (sampling sites 4, 5, and 6) and subsurface drains (sampling site 1, 2 and 3) were sampled in each of these three plots. In addition, water quality was monitored at three other locations (sampling sites 7, 8 and 9) indicated in Figure 2. These locations were the Central Sump, which collects water outflows from all subsurface drains, the South Sump, which collects water from the large perimeter ditch which encompasses the entire citrus grove, and a check or Control drain, respectively. A diagram of an individual main plot in the Soil-Water-Atmosphere-Plant (SWAP) project is shown in Figure 3. The surface drainage system consisted of shallow water furrows (north-south direction) between two-row beds of citrus trees perpendicular to the subsurface drains. Individual surface runoffs from each main plot were fed through H-flumes and culvert inlets to the field ditches to provide measurement of surface runoff from each block. A perimeter field ditch was constructed to encompass the entire SWAP experimental area, and the Central Sump connects to the perimeter ditch by means of two lateral service ditches which extend 122 m from the east and west sides of the area (Figure 2). The perimeter ditch was constructed with a bottom width of 1.2 m, a one-to-one side slope, and at an average depth of 1.6 m below ground surface with a 0.02 percent grade. During periods of frequent rainfall, this ditch carries the composite of both surface and subsurface runoff to the collection sump (sampling site 8) for pump discharge from the area and serves during periods of infrequent rainfall as a reservoir for irrigation water. The discharge pump located at the South Sump has a 26.5 m^3 per minute capacity for rapid water removal from the perimeter ditch.

A Control plot with subsurface drains was established in August, 1973, on land adjacent to the SWAP citrus grove (Figure 2; sampling site 9) and was maintained in natural sod cover which was mowed occasionally. Three subsurface drains each 100.6 m long were placed at 107 cm depth and spaced 18.3 m apart. This control plot was not planted to citrus, received no tillage, and received no application of agricultural chemicals. For ST, DT, DTL, and Control plots, calibrated weirs located at the outflow of each center drain were used to continuously monitor the volumetric discharge of water with time on a strip-chart recorder. One hundred ml samples of the outflow water from the center drain of the Control plot were collected weekly for both pesticide and nutrient analyses during times of flow and more frequently during periods selected for intensive sampling. Since the Control plot was not irrigated, sampling of this area was largely confined to periods with significant rainfall. Water table wells established midway between the drains in both treated (ST, DT and DTL) and untreated (Control) areas permitted observation and strip-chart recording of the water table depth. For ST, DT, and DTL plots (but not for the Control), surface runoff flumes were also constructed. During periods of surface runoff the height of water discharging through the flume was measured continuously with a strip-chart recorder and water samples were also taken for nutrient and pesticide analyses. A single bulk water sample was obtained from each location for each runoff event. A small pump was operated at a constant flow rate during runoff and this was collected in a 10-liter glass carboy.

The subsurface drains, shown in Figure 3, consisted of continuous lengths of perforated corrugated plastic tubing (10 cm inside diameter) 91.4 m long and spaced 18.3 m apart with a 0.17 percent slope (on each line). Each drain was placed in the soil to a depth of 107 cm below average ground surface at the midpoint along the drain. The bottom half of each drain line was placed on a 10 cm thick envelope of silica gravel and the top half was covered with a 23 cm wide linear strip of polyethylene sheet used to prevent sediment from entering the drain. Water from each drain discharged into a concrete manhole where flow was measured with 12-inch, 30-degree, V-notch weirs and water-stage recorders, and water samples were collected for later analyses (sampling site 7). Water from all of the 54 drains of the citrus grove is conveyed through a 20.3 m diameter drain to the Central Sump where it is discharged by a pump into the lateral and perimeter field ditch drainage system.

During periods of low rainfall and at the beginning of periods selected for intensive monitoring of drainage water quality, irrigations were applied uniformly to ST, DT and DTL plots with full circle, rotary, pop-up sprinklers spaced 9.1 x 15.2 m with one sprinkler centrally located between every four trees in the middle of the two row bed. The irrigation rate was 0.41 cm/hr with a line pressure of 25 kg/cm^2. The sprinkler nozzles were permanently mounted flush with the ground surface and rose up 16.5 cm when discharging under pressure. Since periodic extremes of low and high rainfall are experienced on flatwood soils planted to citrus, soil water management should (Sites et. al., 1964) include a combination of drainage and sprinkler irrigation.

Fertilizer was applied as normally recommended for citrus growing on flatwood soils. Four quarterly applications were made each year during 1973, 1974, and 1975 at a rate and ratio indicated in Table 2. Total annual quantities of N and P applied were 169.52 and 18.48 kg/ha, respectively.

Precipitation, surface runoff, and subsurface drainage were continuously measured during the three-year study period. Detailed hydrologic data during the 3-year period are included in this report as supporting information for short-term (intensive monitoring periods following applications of chemicals and water) and long-term studies. Samples of drainage water for chemical determination of NO_3-N and PO_4-P were taken at weekly intervals during July,

Table 2. Fertilizer N, P, K and Mg applied per hectare to ST, DT and DTL treatments at the SWAP citrus grove near Fort Pierce.

	Quantity of Fertilizer Applied* (kg/ha)			
Date	N	P	K	Mg
Year: 1973				
March 6	42.38	4.62	35.18	6.36
May 15	42.38	4.62	35.18	6.36
August 21	42.38	4.62	35.18	6.36
October 30	42.38	4.62	35.18	6.36
Annual Total	169.52	18.48	140.72	25.44
Year: 1974				
March 14	42.38	4.62	35.18	6.36
May 21	42.38	4.62	35.18	6.36
September 26	42.38	4.62	35.18	6.36
November 14	42.38	4.62	35.18	6.36
Annual Total	169.52	18.48	140.72	25.44
Year: 1975				
March 10	42.38	4.62	35.18	6.36
June 10	42.38	4.62	35.18	6.36
September 5	42.38	4.62	35.18	6.36
November 4	42.38	4.62	35.18	6.36
Annual Total	169.72	18.48	140.72	25.44
Total Application	508.56	55.44	422.16	76.32

*Each application was 530 kg/ha of an 8-2-8-2 commercial fertilizer (8% N, 2% P_2O_5, 8% K_2O and 2% MgO) which contained ammonium nitrate, diammonium phosphate, potassium chloride and magnesium oxide.

1973 until January, 1976, during periods of flow from the South and Central sumps and from the unfertilized Control plot were taken concurrently to monitor the NO_3-N and PO_4-P leaching losses from these sources. Additionally, five intensively - sampled periods were employed in conjunction with irrigations scheduled immediately following grove fertilization. The average length of these periods was 14 days. These intensively sampled periods of water quality study were conducted in March of 1973, May of 1974, February of 1975, March of 1975, and June of 1975.

Water samples were collected with ISCO Model 1391 samplers from subsurface drains and from the Control plot. During the first five days of intensively sampled periods, sampling intervals as small as 2 hours were chosen for the collection of samples. Samples for routine monthly assessment of nutrient levels were collected manually from the drains usually on a weekly basis. However, even during these long-term studies, samples were taken at daily or biweekly intervals during periods immediately following fertilizations and during peak flow periods initiated either by rainfall or by irrigation.

Laboratory Procedures

After collection, samples were divided and frozen for later delivery to the University of Florida Pesticide Research Laboratory in Gainesville for pesticide analyses. Samples to be analyzed for NO_3-N and PO_4-P concentrations were usually analyzed soon after collection in the field; however, immediate analysis was not always possible. In that case, three drops of chloroform were added to each 100 ml sample as a preservative and the samples were then frozen and stored in a freezer.

NO_3-N and PO_4-P analyses were performed with a Technicon Autoanalyzer II system using two single-channel colorimeters with a recorder. Nitrates were determined using the cadmium reduction procedure (Technicon Industrial Method No. 100-70W). Ortho-phosphate was determined using the ascorbic acid procedure (Technicon Industrial Method No. 94-70W).

Monthly means of water flow and nutrient movement were calculated to determine the long-term trends. While actual data points were shown for the intensive studies, total discharges for water and nutrients were determined graphically by measuring the area beneath each curve of discharge flux.

RESULTS AND DISCUSSION

Long Term Investigation

Rainfall was recorded daily at the SWAP citrus grove near Fort Pierce, Florida for 1973 (Table 3), 1974 (Table 4), and 1975 (Table 5). Total rainfall amounts for 1973, 1974, and 1975 were 134.6, 124.9, and 116.4 cm. Total irrigation amounts were 20.6, 38.7, and 29.7 cm for 1973, 1974, and 1975, respectively (Table 6). Thus the total quantities of irrigation plus rainfall were 155.2, 163.5 and 146.0 cm for 1973, 1974, and 1975, respectively. The six-month periods from May through October was consistently characterized by disproportionately large amounts of rainfall. The total rainfall occurring during these six-month periods represented 79, 82, and 74% of the total rainfall occurring during 1973, 1974, and 1975. Distributions of daily rainfall, however, were very nonuniform for each of the years.

Mean monthly discharges of water, NO_3-N, and PO_4-P with subsurface drainage from ST, DT, and DTL plots are presented in Tables 6-8 and are plotted with time in Figs. 4, 5, and 6 for 1973, 1974, and 1975. Monthly water discharged from the ST treatment was consistently larger than from the deep-tilled plots. During 1973 monthly water discharged from the DT treatment was considerably larger than from DTL; however, during 1974 and 1975, subsurface drainage from the DT plot was only slightly greater than from DTL. The decreased water discharged from the deep-tillage treatments relative

Table 3. Rainfall recorded daily at the SWAP citrus grove near Fort Pierce, Florida during 1973.

Date	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	1973 Rainfall (cm)											
1								0.05		0.23	0.97	
2		0.58		0.08				1.80				
3		0.86						0.10	1.55			
4					1.57			2.67	0.05	0.69		
5				0.76				3.61		0.64		0.03
6							0.61	1.17			0.23	
7						4.57						0.03
8				3.43		0.71	0.23			1.93		1.17
9		2.29	1.91		2.46		1.73	0.61		1.24		
10	0.38	0.43			0.10		0.84		0.03	1.78		0.38
11	1.83							2.44	0.03	0.41		
12	0.41								0.10		0.15	
13		0.03					1.73	0.08			0.05	
14		0.03				0.10	2.41					
15		0.15			0.81			4.24		0.51		
16						1.98						
17			0.33			1.65			0.56			1.04
18		0.66				1.57			2.03	0.71		
19		0.08				2.62			1.07	4.85	0.13	
20			0.05			0.86			0.69	4.65		
21			0.38				1.27	1.52			0.33	0.61
22	1.14					0.30	1.52	2.06		1.60		
23	1.19					1.04	1.04		3.99		0.10	
24	1.07				0.86		0.30		1.27	0.94		
25			2.72		5.26			2.54	0.66			
26				0.48				0.20				
27	0.74					1.40			1.09			
28	0.64						3.18	0.05	0.08			0.28
29					0.79		1.91	0.28		0.13		
30					1.85		1.78					
31								0.51				
TOTAL	7.40	5.11	5.39	4.75	13.70	16.80	18.55	23.93	13.20	20.31	1.96	3.54

Table 4. Rainfall recorded daily at the SWAP citrus grove near Fort Pierce, Florida during 1974.

Date	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						1974 Rainfall (cm)						
1			0.36				0.46			0.28	0.64	
2				1.91		0.64	3.51	0.56	0.94			0.30
3						2.03	0.89	0.03		3.48		
4							0.56				0.13	
5				0.25	1.91		0.56	3.56	2.06			
6				0.38	1.63			0.97	1.04			
7	0.10							0.05		4.39		
8	0.03						3.07	0.08		0.10		
9		0.08							0.79			
10						3.81						
11						1.57			0.28		0.36	
12								1.91				
13					1.14			1.47				
14	5.56		0.38			0.56				0.13		
15	0.13		2.03		5.59		2.72					
16				0.89		6.91	0.91					1.68
17							1.47		0.10			2.74
18		0.91					0.79				0.23	
19								0.89			0.13	
20		0.51				0.51		2.18				
21												
22							0.15		0.20			
23				2.16		1.65	0.81					
24						1.40			1.57	0.20		
25	0.20					9.78	0.20					0.18
26						2.03	0.28	2.36				
27						2.36		0.28	1.32		1.04	
28						0.36						
29						0.46	4.34					
30							1.57		3.40			
31							0.08			0.38		
TOTAL	6.02	1.50	2.77	5.59	10.27	34.07	22.37	14.34	11.70	8.96	2.53	4.73

Table 5. Rainfall recorded daily at the SWAP citrus grove near Fort Pierce, Florida during 1975.

Date	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
					1975 Rainfall (cm)							
1							0.64	0.05	0.51			
2						1.02	1.52		1.40	1.09		
3						0.15	0.23			0.10	0.76	
4					0.38	0.25					0.30	
5	0.20		1.27		1.14					0.89		
6		0.94							0.89	0.15	0.23	
7					3.00	0.64					0.10	0.28
8						0.13		[illegible]	1.02			
9		0.38			0.89	0.64	0.38	[illegible]	3.56			0.33
10		0.74					0.51		2.03		0.74	
11		0.74		1.40		0.51	0.38	0.25	1.37		0.05	
12												
13	0.10				1.40			2.67		0.05		0.89
14	0.66			0.20			1.80	1.65		0.03	0.13	0.43
15				0.05		0.25	0.05	0.33	0.13	0.15		
16				2.44	4.83	0.13	0.05					
17					1.40	0.15	0.05					
18			0.64		0.89				3.18	1.52		
19			2.29		0.64	2.41		0.13	0.64		0.51	
20	0.25							0.30		0.25	4.85	
21		2.79					0.05		0.13			0.91
22									1.27			
23		4.38				0.15			1.35	0.33		
24						1.80						
25						0.43			0.13			
26							1.40		0.43			0.20
27							0.13			1.02		
28					2.34		1.78	0.76	3.56			
29					9.40	2.03	0.58	0.38	1.52	0.05		
30						0.76			1.65			
31							0.25					0.05
TOTAL	1.21	9.97	4.20	4.09	26.31	11.45	9.80	8.18	24.77	5.63	7.67	3.09

Table 6. Mean monthly concentrations and total discharges of NO_3-N and PO_4-P per hectare in subsurface drainage water in the ST soil management treatment during 1973-1975 as a function of rainfall, total drainage, and water table height.

Year	Month	Rain (cm)	Irrigation (cm)	Water[a] Table Height (m)	Water Flow (m^3/ha)	NO_3-N (Kg/ha)	PO_4-P (Kg/ha)	NO_3-N (ug/ml)	PO_4-P (ug/ml)
1973	Jan	7.40	1.42	5.30	420.70	2.610	a	6.20	a
	Feb	5.11	0	5.30	362.80	.580	a	1.60	a
	March	5.39	3.39	5.27	253.90	.520	a	2.05	a
	April	4.75	3.62	5.27	159.20	.550	a	3.45	a
	May	13.70	3.47	5.30	365.40	1.750	.066	4.80	.18
	June	16.80	0	5.39	995.40	9.660	.438	9.70	.44
	July	18.55	1.48	5.43	1034.26	6.250	.486	6.30	.47
	Aug	23.93	3.99	5.58	2147.57	4.158	.981	1.94	.46
	Sept	13.20	0	5.46	1093.32	3.354	.869	3.07	.80
	Oct	20.31	0	5.46	1376.43	1.998	.881	1.45	.64
	Nov	1.96	1.56	5.27	95.59	.040	.019	.42	.20
	Dec	3.54	1.65	5.21	26.70	.011	.005	.42	.20
	Total	134.64	20.58	5.35	8331.30	31.751	3.745	3.81	.45
1974	Jan	6.02	1.63	5.30	371.74	.283	.011	.76	.03
	Feb	1.50	3.39	5.21	0.49	.001	.000	1.94	.35
	March	2.77	18.10	5.33	1115.79	14.257	.367	12.78	.32
	April	5.59	1.99	5.18	0.34	.001	.000	4.38	.06
	May	10.27	9.73	5.30	882.45	7.165	.215	8.12	.25
	June	34.07	0	5.49	2093.68	15.601	.776	7.45	.37
	July	22.37	0	5.49	1658.14	4.306	.619	2.60	.37
	Aug	14.34	0	5.39	834.61	.572	.588	.68	.70
	Sept	11.70	0	5.30	337.86	.051	.181	.14	.48
	Oct	9.96	1.97	5.39	930.48	3.989	.310	4.29	.33
	Nov	2.53	1.85	5.21	2.69	.002	.001	.70	.21
	Dec	4.73	0	5.27	203.11	1.989	.071	9.79	.35
	Total	124.85	38.66	5.32	8470.38	48.217	3.132	5.69	.37
1975	Jan	1.21	1.81	5.21	0.13	.000	.000	.06	.25
	Feb	9.97	5.92	5.38	825.52	4.194	.133	5.08	.16
	March	4.20	2.44	5.32	391.63	.901	.063	2.30	.15
	April	4.09	5.57	5.28	169.86	.806	.022	4.75	.13
	May	26.31	1.93	5.41	1536.24	5.711	.362	3.72	.24
	June	11.45	3.89	5.40	807.54	4.962	.222	6.14	.27
	July	9.80	1.69	5.28	328.26	2.187	.100	6.66	.30
	Aug	8.18	1.14	5.27	178.68	.702	.051	3.93	.29
	Sept	24.77	0	5.43	1299.06	16.991	.830	13.08	.64
	Oct	5.63	1.67	5.34	577.74	7.794	.516	13.49	.89
	Nov	7.67	1.79	5.27	282.68	1.160	.161	4.13	.56
	Dec	3.09	1.81	5.26	41.20	.246	.014	5.96	.33
	Total	116.37	29.66	5.32	6438.54	45.653	2.467	7.09	.38

[a] PO_4-P was not determined on these samples.

[a] The elevation of the soil surface was 6.40 m above mean sea level.

Table 7. Mean monthly concentrations and total discharges of NO_3-N and PO_4-P per hectare in subsurface drainage water in the DT soil management treatment during 1973-1975 as a function of rainfall, total drainage, and mean water table height.

Year	Month	Rain (cm)	Irrigation (cm)	Water[c] Table Height (m)	Water Flow (m^3/ha)	NO_3-N (Kg/ha)	PO_4-P (Kg/ha)	NO_3-N (ug/ml)	PO_4-P (ug/ml)
1973	Jan	7.40	1.42	5.43	331.0	1.026	a	3.10	a
	Feb	5.11	0	5.39	270.4	0.314	a	1.16	a
	March	5.39	3.39	5.30	102.4	0.133	a	1.30	a
	April	4.75	3.62	5.24	75.4	0.139	a	1.84	a
	May	13.70	3.47	5.27	221.6	0.525	0.018	2.37	0.07
	June	16.80	0	5.55	805.9	4.191	b	5.20	b
	July	18.55	1.48	5.58	804.0	2.565	b	3.19	b
	Aug	23.93	3.99	5.76	1576.2	1.245	0.259	0.79	0.16
	Sept	13.20	0	5.64	749.8	0.101	0.174	0.13	0.23
	Oct	20.31	0	5.67	811.2	0.093	0.218	0.11	0.27
	Nov	1.96	1.56	5.36	162.9	0.030	0.008	0.18	0.05
	Dec	3.54	1.65	5.24	30.9	0.004	0.018	0.12	0.06
	Total	134.64	20.58	5.45	5849.8	10.364	0.679	1.77	0.11
1974	Jan	6.02	1.63	5.36	194.37	0.126	0.011	0.65	0.05
	Feb	1.50	3.39	5.21	14.44	0.005	0.003	0.32	0.20
	March	2.77	18.10	5.52	589.43	0.655	0.075	1.11	0.13
	April	5.59	1.99	5.27	58.43	0.014	0.008	0.24	0.14
	May	10.27	9.73	5.43	357.98	0.543	0.023	1.52	0.06
	June	34.07	0	5.67	871.21	0.858	0.091	0.99	0.10
	July	22.37	0	5.82	1259.00	1.146	0.113	0.91	0.09
	Aug	14.34	0	5.70	502.52	0.121	0.201	0.24	0.40
	Sept	11.70	0	5.42	147.28	0.026	0.029	0.18	0.20
	Oct	8.96	1.97	5.55	364.73	0.242	0.141	0.66	0.39
	Nov	2.53	1.85	5.24	18.16	0.001	0.007	0.05	0.38
	Dec	4.73	0	5.33	5.84	0.001	0.002	0.09	0.42
	Total	124.85	38.66	5.46	4383.42	3.737	0.705	0.83	0.16
1975	Jan	1.21	1.81	5.17	0.00	0.000	0.000	0.00	0.00
	Feb	9.97	5.92	5.37	64.29	0.000	0.001	0.01	0.01
	March	4.20	2.44	5.45	182.51	0.011	0.000	0.06	0.00
	April	4.09	5.57	5.35	130.26	0.016	0.000	0.12	0.00
	May	26.31	1.93	5.50	454.68	0.064	0.000	0.14	0.00
	June	11.45	3.89	5.60	531.96	0.084	0.000	0.16	0.00
	July	9.80	1.69	5.36	198.42	0.028	0.000	0.14	0.00
	Aug	8.18	1.14	5.26	102.73	0.012	0.000	0.14	0.00
	Sept	24.77	0	5.50	433.32	0.076	0.000	0.18	0.00
	Oct	5.63	1.67	5.52	340.38	0.035	0.010	0.10	0.03
	Nov	7.67	1.79	5.37	148.08	0.010	0.004	0.07	0.03
	Dec	3.09	1.81	5.31	59.46	0.021	0.000	0.35	0.00
	Total	116.37	28.66	5.40	2646.09	0.358	0.015	0.14	0.01

[a] PO_4-P was not determined on these samples.

[b] These discharge values were less than 0.01 kg of NO_3-N.

[c] The elevation of the soil surface was 6.28 m above mean sea level.

Table 8. Mean monthly concentrations and total discharges of NO_3-N and PO_4-P per hectare in subsurface drainage water in the DTL soil management treatment during 1973-1975 as a function of rainfall, total drainage, and mean water table height.

Year	Month	Rain (cm)	Irrigation (cm)	Water* Table Height (m)	Water Flow (m^3/ha)	NO_3-N (kg/ha)	PO_4-P (kg/ha)	NO_3-N (ug/ml)	PO_4-P (ug/ml)
1973	Jan	7.40	1.42	5.58	133.23	0.510	a	3.80	a
	Feb	5.11	0	5.58	114.94	0.210	a	1.80	a
	March	5.39	3.39	5.46	42.69	0.080	a	1.90	a
	April	4.75	3.62	5.43	30.54	0.070	a	2.45	a
	May	13.70	3.47	5.43	83.17	0.250	0.005	3.00	0.06
	June	16.80	0	5.64	444.18	4.490	b	10.10	b
	July	18.55	1.48	5.70	221.25	0.890	b	4.00	b
	Aug	23.93	3.99	5.97	780.97	1.248	0.124	1.60	0.16
	Sept	13.20	0	5.85	564.07	0.155	0.108	0.27	0.19
	Oct	20.31	0	5.88	519.18	0.050	0.091	0.10	0.18
	Nov	1.96	1.56	5.55	33.57	0.165	0.005	0.49	0.14
	Dec	3.54	1.65	5.36	0.07	[illegible]	0.000	0.49	0.14
	Total	134.64	20.58	5.62	2968.66	7.970	0.332	2.68	0.13
1974	Jan	6.02	1.63	5.46	93.14	0.084	0.009	0.90	0.10
	Feb	1.50	3.39	5.33	0.07	0.000	0.000	1.69	0.29
	March	2.77	18.10	5.67	501.02	5.139	0.111	10.26	0.22
	April	5.59	1.99	5.39	0.16	0.000	0.000	2.10	0.14
	May	10.27	9.73	5.49	280.04	3.329	0.021	11.89	0.08
	June	34.07	0	5.82	809.79	3.411	0.122	4.21	0.15
	July	22.37	0	5.97	652.81	0.905	0.252	1.39	0.39
	Aug	14.34	0	5.82	296.94	0.123	0.146	0.41	0.49
	Sept	11.70	0	5.55	75.35	0.015	0.017	0.20	0.23
	Oct	8.96	1.97	5.67	338.74	0.330	0.177	0.97	0.52
	Nov	2.53	1.85	5.38	0.02	0.000	0.000	0.18	0.22
	Dec	4.73	0	5.43	12.50	0.003	0.006	0.23	0.50
	Total	124.85	38.66	5.58	3060.58	13.339	0.862	4.36	0.28
1975	Jan	1.21	1.81	5.29	0.00	0.000	0.000	0.00	0.00
	Feb	9.37	5.92	5.46	233.64	0.149	0.003	0.64	0.02
	March	4.20	2.44	5.56	105.29	0.094	0.000	0.89	0.00
	April	4.09	5.57	5.45	26.47	0.003	0.000	0.12	0.00
	May	26.31	1.93	5.58	426.10	0.971	0.000	2.28	0.00
	June	11.45	3.89	5.76	371.31	0.316	0.000	0.85	0.00
	July	9.80	1.69	5.49	80.05	0.082	0.000	1.02	0.00
	Aug	8.18	1.14	5.38	12.12	0.015	0.000	0.12	0.00
	Sept	24.77	0	5.65	372.68	1.229	0.014	3.30	0.04
	Oct	5.63	1.67	5.72	219.53	0.669	0.019	3.05	0.09
	Nov	7.67	1.79	5.53	83.70	0.120	0.007	1.43	0.09
	Dec	3.09	1.81	5.45	12.03	0.013	0.001	1.06	0.09
	Total	116.37	29.66	5.53	1942.92	3.646	0.044	1.88	0.02

[a] PO_4-P was not determined on these samples.

[b] These PO_4-P concentrations were less than 0.04 μg/ml.

*The elevation of the soil surface was 6.40 m above mean sea level

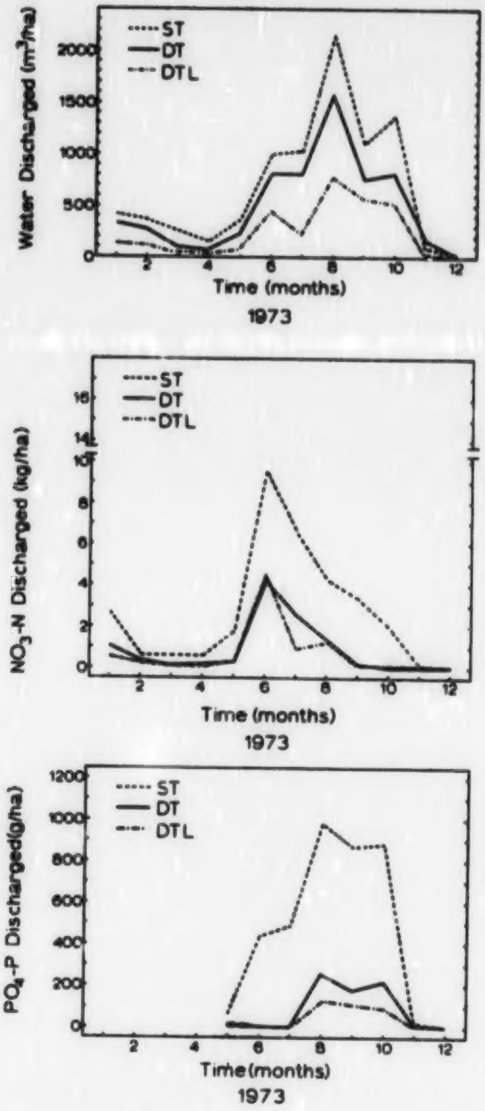


FIGURE 4. Total monthly discharges of drainage water, NO_3-N, and PO_4-P from ST, DT, and DTL soil management plots plotted with time for 1973.

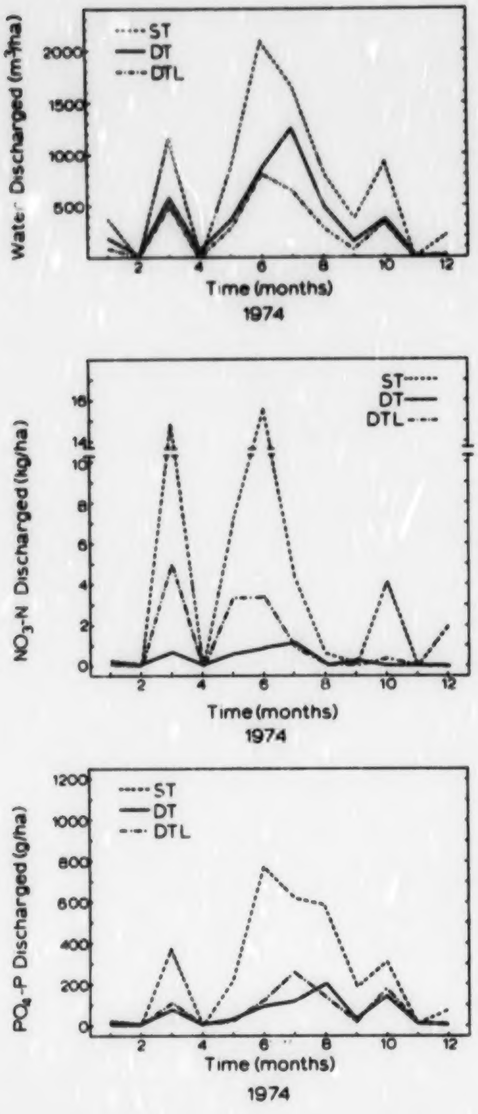


FIGURE 5. Total monthly discharges of drainage water, NO_3-N and PO_4-P from ST, DT, and DTL soil management plots plotted with time for 1974.

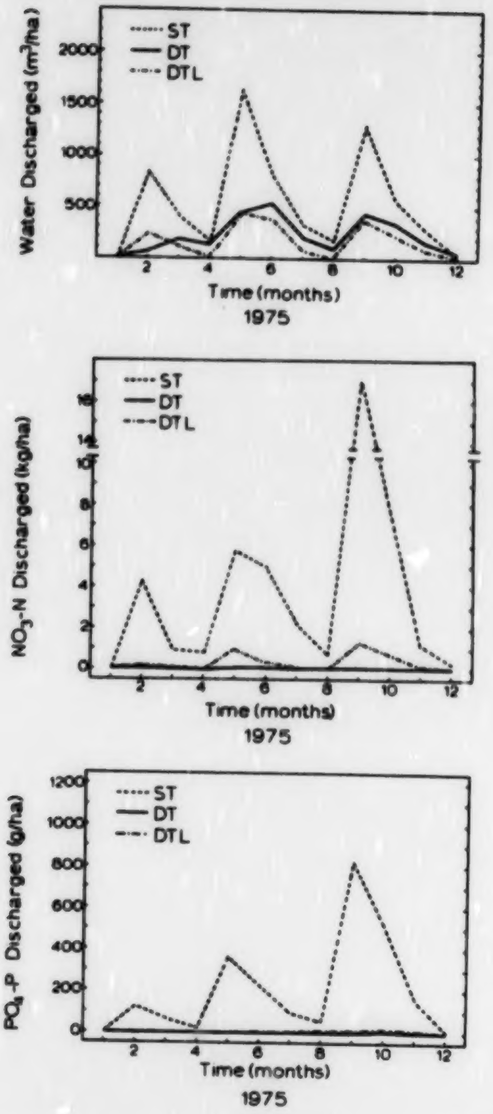


FIGURE 6. Total monthly discharges of drainage water, NO_3-N and PO_4-P from ST, DT, and DTL soil management plots plotted with time for 1975.

to the ST plot was observed earlier by Stewart and Alberts (1971) and can be explained primarily by two phenomena: a decrease in the hydraulic conductivity (Hammond et al., 1971) of the soil (0-85 cm depth) occurred due to mixing of subsoil spodic and sandy clay horizons with the sandy surface (A_1 and A_2 horizons) soil and a partial "clogging" of the flow medium in the immediate vicinity of DT and DTL drains was observed (Rogers, 1971 and Rogers and Stewart, 1974). Using an electrical analog, Rogers (1971) showed that if "clogging" had not have occurred drainage flows from DT and DTL plots should have exceeded that for ST due to the greater effective volume of soil drained. The "clogging" of DT and DTL drains has been partially attributed to the deposition of suspended and dissolved colloidal organic matter in the porous material immediately surrounding the drain tubes following the deep tillage operation. Fiskell et al. (1970) have shown experimentally that under conditions of low soluble salts organic matter can be partially dissolved and move with soil water for Oldsmar fine sand. By increasing the level of soluble salts either in the soil or in the infiltrating water mobility of the organic material could be suppressed by preventing flocculation of the negatively charged colloids. The mechanical action of the deep tillage operation in conjunction with heavy rainfall which occurred soon afterwards probably resulted in the transport of suspended and dissolved organic material with water toward the drain tubes where deposition and/or filtering occurred. Activity of soil microorganisms is also another possible contribution to the "clogging" effect of the drains. The overall effects of the decreased drainage flow in the deep-tilled plots relative to the shallow-tilled plot were decreased infiltration rates which increased the probability for surface runoff during intense rainfall and decreased time-response for removal of excess water from the root zone of the soil following a large rainfall event. The slower drainage response in DT and DTL plots also tended to provide higher soil water contents at a given time than in the ST plot. Hammond et al. (1971) also found that the water-holding capacity of the deep-tilled soils were slightly higher than for the shallow-tilled soil.

Periods of greatest monthly discharges of water, NO_3-N and PO_4-P in subsurface drains from ST, DT, and DTL plots (Figs. 4, 5, and 6) were generally associated with periods of greatest monthly rainfall (Tables 6, 7, and 8). Discharge of water, NO_3-N, and PO_4-P occurred during March and May through October for 1973, during March and May through October for 1974, and February, May-July, and September-October for 1975. In all cases discharge of water and nutrients was much higher from ST than from either DT or DTL plots. The greater water flows through the ST soil and out into the drain tubes resulted in much greater losses of NO_3-N and PO_4-P with subsurface drainage than for DT and DTL treatments. Mean monthly discharge of both NO_3-N and PO_4-P with drainage water occurred in the order: ST > DTL $\geq$ DT. Although the water flow in DT drains usually exceeded that from DTL, discharge of NO_3-N with drainage was frequently greater from the DTL plot. Discharge of PO_4-P in drainage was usually similar for DT and DTL plots. Total quantities of NO_3-N discharged with subsurface drainage during 1973, 1974, and 1975 were 31.75, 48.22, and 45.77 kg/ha for the ST plot (Table 6); 7.97, 13.34, and 3.65 kg/ha for DTL (Table 8); and 10.36, 3.74, and 0.36 kg/ha for DT (Table 7).

Discharge of PO_4-P with subsurface drainage was always several-fold less than NO_3-N discharge for all three soil management treatments. Total amounts of PO_4-P discharged in subsurface drainage during 1973, 1974, and 1975 were 3.75, 3.14, and 2.47 kg/ha for the ST plot; 0.33, 0.86, and 0.04 kg/ha for DTL; and 0.68, 0.70, and 0.01 kg/ha for DT (Tables 6, 7, and 8). The total quantity of N applied each year was 9.2 times larger than that for P. The ratios of the quantities of NO_3-N actually discharged with drainage to the quantities of PO_4-P discharged varied considerably from 9.2. During 1973-1975 the ratio of NO_3-N to PO_4-P increased from 8.5 to 18.5 for the ST plot. During the same period this same ratio also decreased from 13.7 to 3.8 for the DT plot, and decreased from 18.6 to 15.2 for DTL. Although many factors affect this ratio, an increase in the ratio possibly indicates an increase in NO_3-N discharge with a corresponding discharge of PO_4-P. Detailed interpretation of these changes in the ratios of NO_3-N and PO_4-P discharges is not attempted at this time.

Monthly discharge amounts of NO_3-N and PO_4-P in drainage from ST, DT, and DTL plots is presented in Table 9 for six wet months (May-October) and in Table 10 for six dry months (November-April) for the period 1973-1975. These data are in agreement with the findings of Calvert and Phung (1971) who observed that NO_3-N loss with drainage water was much greater during periods of high rainfall and thus high drainage discharge. Later Calvert (1975) concluded that maximum discharge as well as concentration of fertilizer nutrients was greatly dependent upon rainfall plus irrigation amounts and upon timing of fertilizer applications with respect to the average rainfall distribution.

The highest mean monthly concentrations of NO_3-N in drainage from the ST plot were found for the ST drainage during the wet seasons for these three years. Subsurface drainage water from the DTL plot actually developed higher NO_3-N concentrations during 1973 and 1974 wet seasons than did water from the ST drain. This result may be attributed to a greater nitrification rate in DTL than in ST and DT soil treatments (Phung, 1972). Only in the wet 1974 year was concentration of NO_3-N from DTL higher than from the ST drain during the dry season. The NO_3-N concentration in ST drain water in the dry months within the three years ranged from 0.39 to 6.2 μg/ml. The unusually high discharge of NO_3-N from ST that occurred in the wet season of 1975 is believed to have been influenced by two major rainfall events which occurred in May and September. The rainfall distribution in 1975 was such that 26% of the annual rainfall (116.4) occurred during the dry six-month period as compared to only 21% (134.6 cm annual rainfall) and 19% (124.9 cm rainfall) during 1973 and 1974, respectively. Discharge of PO_4-P was considerably less than discharge of NO_3-N, but more PO_4-P was leached from the ST soil profile relative to DT and DTL and discharged from the drain during each of the three years of the study. DT and DTL drains usually discharged disimilar amounts of NO_3-N, but similar amounts of PO_4-P into the drain water.

Maximum discharge of PO_4-P occurred from the ST drain during the high rainfall months of 1973 and 1974 (Figs. 9 and 10). Substantial discharges of PO_4-P occurred from DT and DTL plots only in the rainy periods of 1973 and 1974, but virtually no discharge of PO_4-P occurred from these plots

Table 9. Six-month means for NO_3-N and PO_4-P concentrations and discharge in subsurface drainage from ST, DT, and DTL soil management treatments as influenced by rainfall and total drainage. Data for six-month wet periods (May through October) are presented for 1973-1975.

Year	Rainfall	Chemical	Soil Treatment	Drainage*	Chemical Concentration Mean	Chemical Concentration Range	Total Chemical Discharged
	(cm)			(cm)	(µg/ml)	(µg/ml)	(ha)
1973	106.49	NO_3-N	ST	70.12	3.87	1.45-9.70	27.17
		"	DT	49.68	1.76	0.11-5.20	8.72
		"	DTL	26.13	2.71	0.10-10.10	7.08
		PO_4-P	ST	70.12	0.53	0.18-0.80	3.72
		"	DT	49.68	0.13	0.00-0.27	0.67
		"	DTL	26.13	0.12	0.00-0.19	0.33
1974	101.71	NO_3-N	ST	67.37	4.70	0.14-8.12	31.68
		"	DT	35.03	0.84	0.18-1.52	2.94
		"	DTL	24.54	3.31	0.20-11.89	8.11
		PO_4-P	ST	67.37	0.40	0.25-0.70	2.69
		"	DT	35.03	0.16	0.06-0.40	0.58
		"	DTL	24.54	0.30	0.08-0.49	0.74
1975	86.14	NO_3-N	ST	47.28	8.11	3.72-13.49	38.35
		"	DT	20.61	0.14	0.10-0.18	0.30
		"	DTL	14.82	2.21	0.12-3.30	3.28
		PO_4-P	ST	47.28	0.44	0.24-0.89	2.08
		"	DT	20.61	0.00	0.00-0.03	0.01
		"	DTL	14.82	0.02	0.00-0.09	3.03

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*One cm of drainage is equivalent to 100 M^3/ha.

Table 10. Six-month means for NO_3-N and PO_4-P concentrations and discharge in subsurface drainage from ST, DT, and DTL soil management treatments as influenced by rainfall and total drainage. Data for six-month dry periods November through April) are presented for 1973-1975.

Year	Rainfall (cm)	Chemical	Soil Treatment	Drainage* (cm)	Chemical Mean (µg/ml)	Concentration Range (µg/ml)	Total Chemical Discharged (ha)
1973	28.15	NO_3-N	ST	13.19	3.28	0.42-6.20	4.33
		"	DT	9.73	1.69	0.12-3.10	1.65
		"	DTL	3.55	2.92	0.49-3.80	1.04
		PO_4-P	ST	13.19	0.52	0.47-0.57	0.07
		"	DT	9.73	0.12	0.08-0.16	0.02
		"	DTL	3.55	0.17	0.16-0.18	0.01
1974	23.14	NO_3-N	ST	16.94	9.76	0.70-12.78	16.53
		"	DT	8.81	0.91	0.05-1.11	0.80
		"	DTL	6.07	8.61	0.18-10.26	5.23
		PO_4-P	ST	16.94	0.26	0.03-0.35	0.45
		"	DT	8.81	0.12	0.05-0.42	0.11
		"	DTL	6.07	0.21	0.10-0.50	0.13
1975	30.23	NO_3-N	ST	17.11	4.30	0.06-5.96	7.31
		"	DT	5.85	0.10	0.01-0.35	0.06
		"	DTL	4.61	0.82	0.12-1.43	0.38
		PO_4-P	ST	17.11	0.23	0.13-0.56	0.39
		"	DT	5.85	0.01	0.00-0.03	0.01
		"	DTL	4.61	0.02	0.00-0.09	0.01

*One cm of drainage is equivalent to 100 M^3/ha.

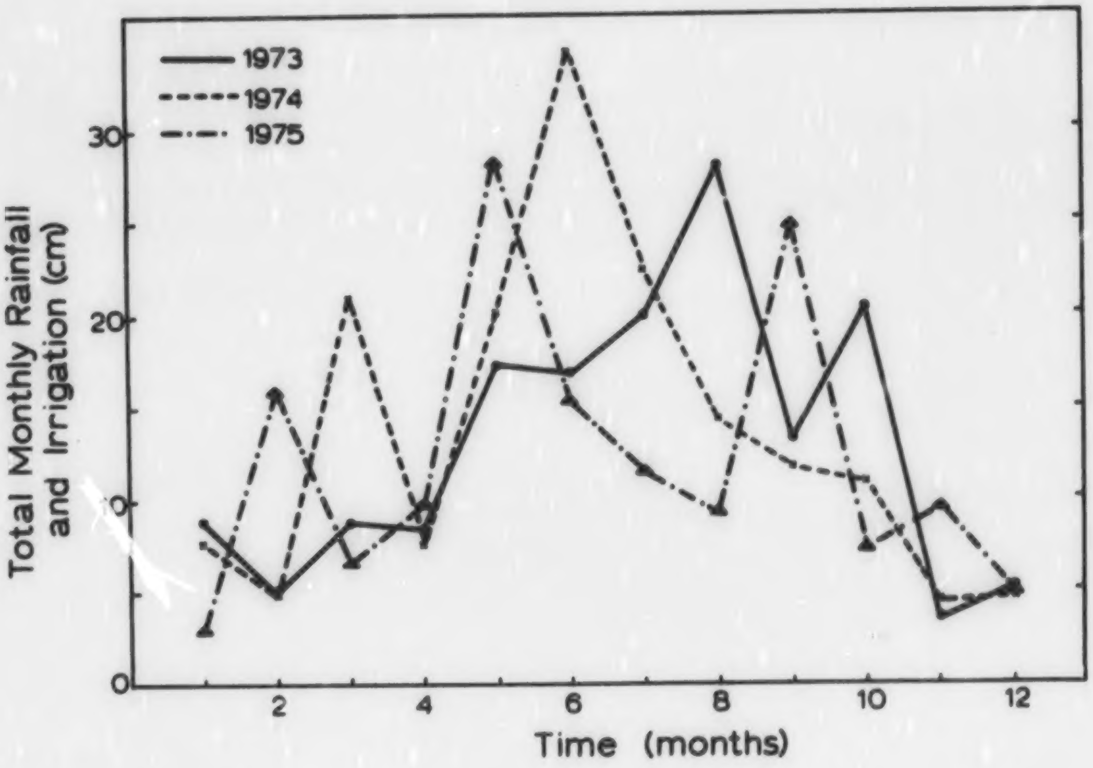


FIGURE 7. Total monthly amounts of rainfall and irrigation for ST, DT, and DTL plots plotted with time for the period 1973-1975.

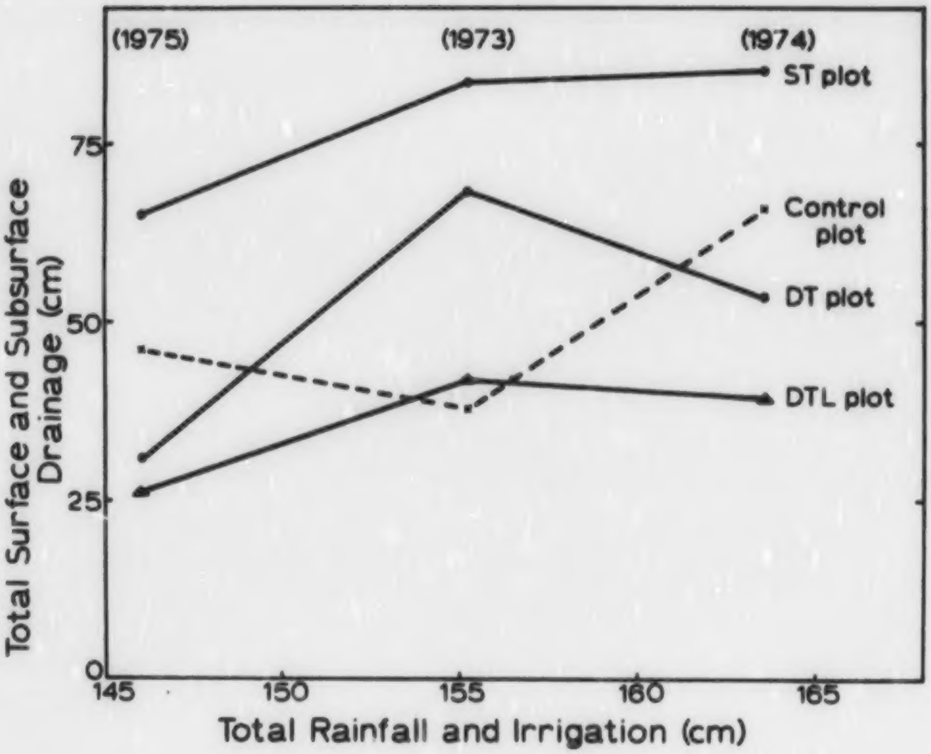


FIGURE 8. Total annual quantities of surface and subsurface drainage plotted versus total amounts of rainfall plus irrigation for ST, DT, DTL, and Control soil management plots for the period 1973-1975.

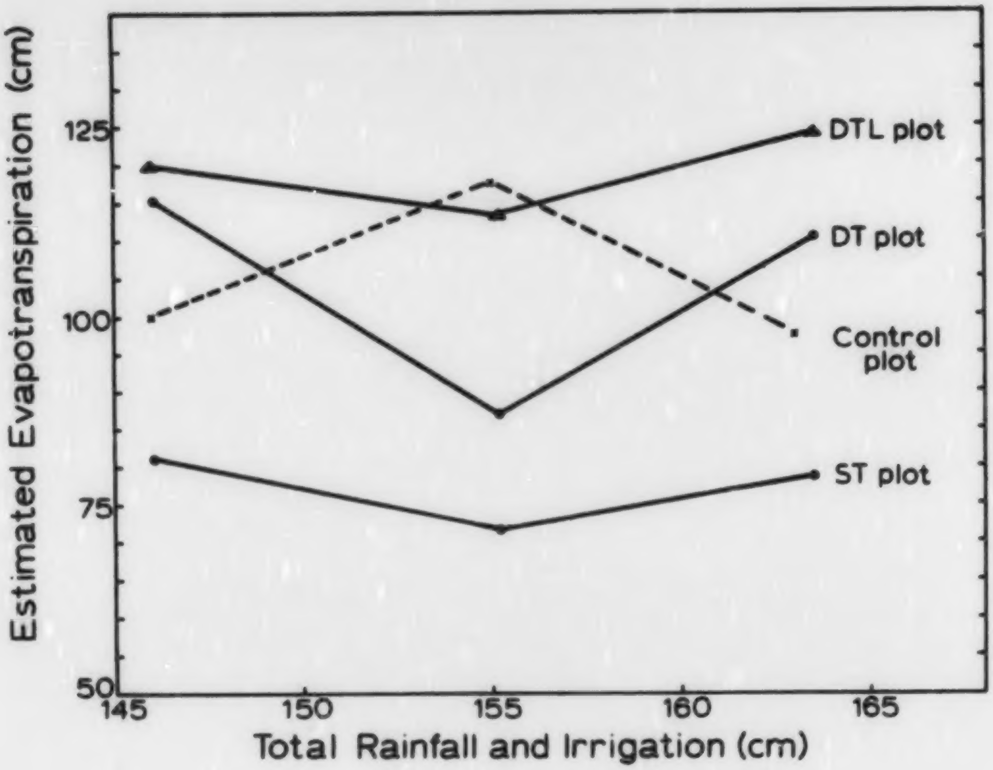


FIGURE 9. Estimated annual amounts of water used in evapotranspiration versus total amounts of rainfall plus irrigation for ST, DT, DTL, and Control soil management plots for the period 1973-1975.

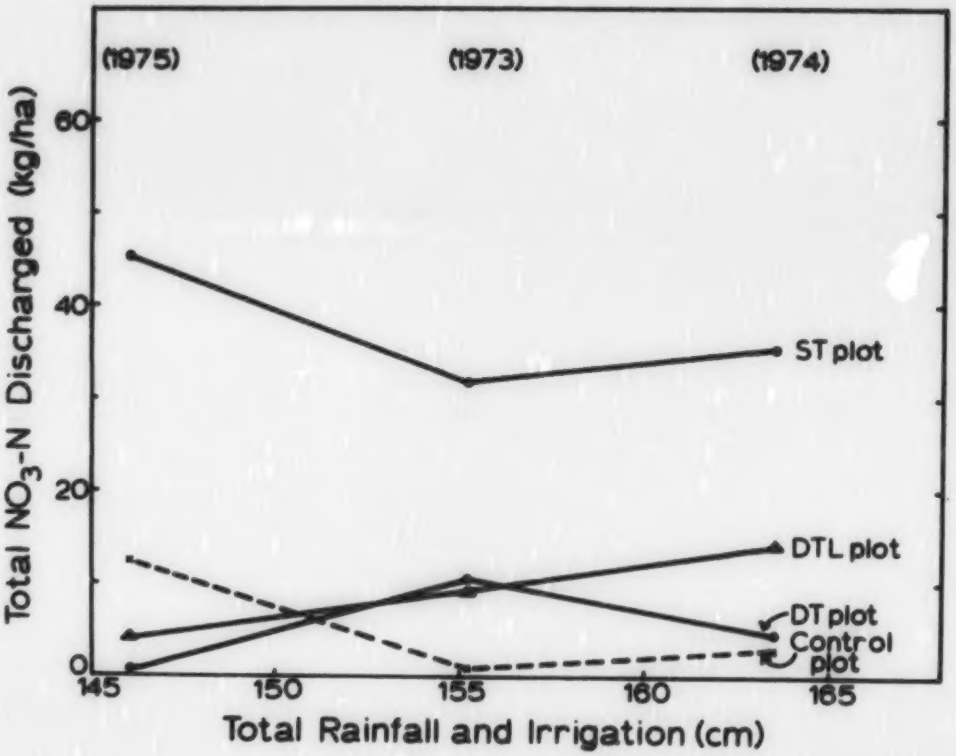


FIGURE 10. Total NO_3-N discharged annually with surface and subsurface drainage water versus total amounts of rainfall plus irrigation for ST, DT, DTL, and Control soil management plots for the period 1973-1975.

during 1975, even in the rainy period. Discharges from DT and DTL in the rainy period of 1975 amounted to less than 0.2 kg/ha/mo of PO_4-P. That amount of PO_4-P was considered to be negligible. Monthly maximum discharges of PO_4-P in drainage from ST were 1.0, 0.8 and 0.8 kg/ha, respectively, in 1973, 1974 and 1975. These maxima occurred in August 1973, June 1974, and September 1975, respectively.

Surface runoff was recorded for each major rain event from September 1973 through December 1975. Surface runoff was largely limited to the DT and DTL plots (Table 11) since the ST plot had an ultimate infiltration rate (see saturated hydraulic conductivity values in Table 1) sufficient to preclude the occurrence of runoff from the surface. Runoff was detected from the ST plot (Table 11) only during extemely high intensity rains. The maximum runoff values for the three years were 0.11, 6.27 and 4.69 cm for ST, DT and DTL plots and occurred in June, 1974, after 34 cm of rainfall. Only 1.7 g of NO_3-N was detected in the total runoff water from ST at this time in contrast to 138 g and 103 g of NO_3-N in the runoff from DT and DTL, respectively (Table 11). Maximum mean concentrations of NO_3-N in composite samples of surface runoff were 3.4 µg/ml for ST in September 1973; 12.4 µg/ml for DT and 12.6 µg/ml for DTL in March 1975. Total discharge of NO_3-N however, was negligible during these times because of very small total flows of water. During 1975, rainfall was low during the normally rainy summer months, and the largest runoff was associated with intensive rainfall events (26.31 cm) in May. Runoff from ST was negligible (0.16 cm) during May and was considerably higher from DT (3.66 cm) and DTL (4.37 cm) (Table 11).

Surface losses of NO_3-N and PO_4-P usually were less than 1% of that applied as fertilizer except in 1974 the PO_4-P loss from the DT and DTL drains amounted to 2.0% and 1.7%, respectively. Loss of NO_3-N from the control line was low except in 1975 when an amount of NO3-N approximating 7.3% of the N applied to the fertilized plots in SWAP was discharged from the unfertilized Control line. Also, the unfertilized Control line discharged sizeable quantities of PO_4-P in 1973 and 1974 which were equivalent to a fertilized plot loss of 4.4 and 5.2%, respectively.

Water quality data obtained in the 3-year study from sampling locations 7, 8 and 9 (Figure 2) at the Central Sump, South Sump, and Control drain, respectively are presented in Table 12. Months having peak water flows from the unfertilized Control plot coincided with peak flows from the Central and South Sumps. Maximum concentrations of NO_3-N in drainage from the Control plot (Table 11) were generally small. During 1973 concentrations of NO_3-N in water from the Control plot were much lower than in drainage from ST, DT and DTL. In 1974 the NO_3-N concentration for the Control was lower than for ST and DTL, but greater than for DT. However, during 1975 NO_3-N concentrations for the Control were much higher than NO_3-N concentrations for both DT and DTL. The reason for the higher NO_3-N concentrations in the drainage from the Control during 1975 is not immediately clear, but presumably some nitrification occurred. Since the Control plot was not fertilized, assay of control drainage water provides a check on the amount of NO_3-N produced by natural means such as nitrification of organic matter and nitrate fixation during electrical activity from thunderstorms.

Table 11. Mean monthly concentrations and total discharges of NO_3-N and PO_4-P in surface runoff water from surface tilled (ST), deep tilled (DT) and deep tilled plus limestone (DTL) soil management treatments as a function of rainfall during 1973, 1974, and 1975.

		Surface Tilled					Deep Tilled					Deep Tilled Limed				
Month	Rain fall	Water Runoff	NO_3-N Conc.	PO_4-P Conc.	NO_3-N Disc.	PO_4-P Disc.	Water Runoff	NO_3-N Conc.	PO_4-P Conc.	NO_3-N Disc.	PO_4-P Disc.	Water Runoff	NO_3-N Conc.	PO_4-P Conc.	NO_3-N Disc.	PO_4-P Disc.
	-cm-	m^3/ha	------ppm------		-------g-------		m^3/ha	------ppm------		-------g-------		m^3/ha	------ppm------		-------g-------	
1973																
Sept	13.20	3.97	3.40	0.30	13.50	1.19	108.21	1.53	0.30	165.96	32.46	203.80	4.54	0.36	985.25	73.37
Oct	20.31	2.80	1.00	0.20	2.80	0.96	357.14	0.44	0.20	157.14	71.43	287.52	0.80	0.30	230.02	86.26
Nov	1.96	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dec	3.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1974																
Jan	6.02	0.25	0.00	0.00	0.00	0.00	6.12	0.00	0.00	0.00	0.00	10.17	0.00	0.00	0.00	0.00
Feb	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mar	2.77	0.00	0.00	0.00	0.00	0.00	98.38	4.06	0.59	399.42	58.04	119.13	3.56	0.60	424.10	71.48
Apr	5.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	nsnf	nsnf	0.00	0.00
May	10.27	3.48	0.30	0.10	1.04	0.35	20.96	3.72	0.74	77.97	15.51	55.36	3.76	0.44	208.15	24.36
June	34.07	10.67	0.16	0.22	1.71	2.35	626.67	0.22	0.37	137.87	231.87	469.08	0.22	0.31	103.20	145.41
July	22.37	0.57	0.00	0.67	0.00	0.38	137.67	0.46	0.31	63.33	42.68	128.48	0.61	0.23	78.37	29.55
Aug	14.34	0.67	0.00	0.45	0.00	0.30	25.20	0.06	0.41	1.39	9.51	43.13	0.04	0.76	1.73	32.76
Sept	11.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.32	1.08	0.00	0.00
Oct	8.96	1.62	0.30	0.07	0.49	0.11	54.55	0.15	0.27	8.18	14.73	62.06	0.11	0.28	6.83	17.38
Nov	2.53	0.00	0.00	0.00	0.00	0.00	0.00	nsnf	0.00	0.00	0.00	0.00	-0.00	0.00	0.00	0.00
Dec	4.73	0.00	0.00	0.00	0.00	0.00	0.15	nsnf[a]	nsnf	0.00	0.00	1.34	bmdl	bmdl	bmdl	bmdl
1975																
Jan	1.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feb	9.97	1.85	bmdl[b]	bmdl	bmdl	bmdl	28.90	bmdl	bmdl	bmdl	bmdl	74.36	bmdl	bmdl	bmdl	bmdl
Mar	4.20	0.07	nsnf	nsnf	nsnf	nsnf	0.97	12.40	0.25	12.03	0.24	1.66	12.60	0.25	20.92	0.42
Apr	4.09	0.03	nsnf	nsnf	nsnf	nsnf	0.06	nsnf	nsnf	nsnf	nsnf	0.23	nsnf	nsnf	nsnf	nsnf
May	26.31	16.00	0.89	0.46	14.24	7.36	366.00	0.64	0.34	234.24	124.44	437.00	0.93	0.34	406.41	148.58
June	11.45	0.15	nsnf	nsnf	nsnf	nsnf	1.48	0.20	1.40	0.30	2.07	0.79	0.27	2.80	0.21	2.21
July	9.80	0.05	nsnf	nsnf	nsnf	nsnf	0.07	nsnf	nsnf	nsnf	nsnf	0.28	0.65	0.88	0.18	0.25
Aug	8.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16	nsnf	nsnf	nsnf	nsnf
Sept	24.77	3.30	0.20	1.22	0.66	4.03	41.75	0.17	0.54	7.10	22.55	139.20	0.08	0.51	11.14	70.99
Oct	5.63	0.03	nsnf	nsnf	bmdl	bmdl	1.20	0.18	2.01	0.22	2.41	2.44	0.14	0.61	0.34	1.49
Nov	7.67	1.80	1.39	0.20	2.90	0.36	1.96	0.30	0.30	0.59	0.59	3.75	0.52	0.46	1.95	1.73
Dec	3.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

a nsnf, no samples were taken due to negligible flow.
b bmdl, concentration was below the minimum detection level. Minimum detection levels for NO_3-N and PO_4-P are 0.04 ppm and 0.06 ppm, respectively. Discharge values for concentrations lower than these levels were not calculated.

Drainage from the Control also contained detectable levels (ranged from 0.06 to 0.49 µg/ml) of PO_4-P during at least one month out of each of the three years in the study. Again, as with nitrate, both concentrations and total discharge of PO_4-P from the Control drain appeared to increase for a short period then decrease as both rainfall and total flow increased (Table 12), thus indicating miscible displacement between infiltrated water and the soil solution as flow occurs in the soil.

Significant discharges of NO_3-N and PO_4-P through the South and Central Sumps usually coincided with significant discharge from the subsurface drains from the three soil treatment plots (Table 12).

Monthly distributions of rainfall plus irrigation (Fig. 7) for 1973, 1974, and 1975 were found to be similar in that most of the water was applied during the wet period from May through October. Otherwise, the distributions were dissimilar and nonuniform.

A summary of annual quantities of water and nutrient discharge with surface and subsurface drainage for ST, DT, and DTL plots is given in Table 13 and for the Control in Table 14. During all three years subsurface drainage was much greater from the ST plot relative to that for DT and DTL plots. Surface runoff, however, was much greater for DT and DTL plots relative to that for the ST plot. For the ST plot the total annual quantities of surface and subsurface drainage (Fig. 8) increased with increasing total rainfall plus irrigation. For DT and DTL plots, total drainage first increased with rainfall plus irrigation then decreased. For a given quantity of rainfall plus irrigation the total surface plus subsurface drainage was consistently in the order: ST > DT > DTL. Surface plus subsurface drainage from the Control plot at first decreased with rainfall plus irrigation and then increased.

Annual amounts of evapotranspiration were calculated by subtracting amounts of surface plus subsurface drainage from total inputs of rainfall plus irrigation (Fig. 9). Deep percolation losses of soil water were assumed to be insignificantly small. For any given amount of rainfall plus irrigation, estimates for evapotranspiration were in the order: DTL > DT > ST. Evapotranspiration for the Control plot was usually of the same order as for DT and DTL plots. For ST, DT, and DTL plots evapotranspiration at first decreased with rainfall and then increased. Overall growth and fruit yields for the entire SWAP citrus grove during 1973-1975 were in a similar order as for evapotranspiration, ie. DTL $\geq$ DT > ST. For 1975 average orange yields were 216, 156, and 167 boxes/ha, respectively, for DTL, DT, and ST plots. Average yields of grapefruit during 1975 were 576, 400, 392 boxes/ha, respectively, for DTL, DT, and ST plots. Since these citrus trees were relatively young it is important to keep in mind that transpirational use of water on these three plots occurred by both the citrus trees and Bahia sod located between the rows of citrus. The Control plot, of course, was totally covered by sod.

Annual quantities of NO_3-N and PO_4-P discharged (Figs. 10 and 11) with surface and subsurface drainage were shown to increase with total rainfall plus irrigation for the DTL plot. A similar trend was observed for the DT

Table 12. Mean monthly concentrations and total discharges of NO_3-N and PO_4-P in subsurface drainage water from the unfertilized Control Plot, Central Sump, and South Sump as a function of rainfall, drainage, and water table height (W.T. ht.) during 1973, 1974, and 1975.

Month	Rainfall	Control Drain Total Flow	Control Drain W.T. Ht.	Control Drain NO_3-N Conc.	Control Drain PO_4-P Conc.	Control Drain NO_3-N Disc.	Control Drain PO_4-P Disc.	Center Sump Total Flow	Center Sump NO_3-N Conc.	Center Sump PO_4-P Conc.	Center Sump NO_3-N Disc.	Center Sump PO_4-P Disc.	South Sump Total Flow	South Sump NO_3-N Conc.	South Sump PO_4-P Conc.	South Sump NO_3-N Disc.	South Sump PO_4-P Disc.
	cm	m^3/ha	m	ppm	ppm	kg	kg	m^3/ha	ppm	ppm	kg	kg	m^3/ha	ppm	ppm	kg	kg
1973																	
Jan	7.40	dcni[a]	5.55	dcni	dcni	dcni	dcni	3630	1.76	pcnd[b]	6.06	pcnd	6490	1.58	pcnd	10.25	pcnd
Feb	5.11	dcni	5.72	dcni	dcni	dcni	dcni	3270	1.50	pcnd	4.91	pcnd	4850	1.19	pcnd	5.77	pcnd
Mar	5.39	dcni	5.49	dcni	dcni	dcni	dcni	1800	1.55	pcnd	2.79	pcnd	1600	1.30	pcnd	1.92	pcnd
Apr	6.75	dcni	5.41	dcni	dcni	dcni	dcni	1290	4.80	pcnd	6.19	pcnd	1750	1.80	pcnd	3.15	pcnd
May	13.70	dcni	5.32	dcni	dcni	dcni	dcni	1780	3.20	pcnd	5.70	pcnd	1800	1.50	pcnd	2.70	pcnd
June	16.80	dcni	5.79	dcni	dcni	dcni	dcni	6980	8.00	pcnd	55.86	pcnd	15630	2.30	pcnd	35.95	pcnd
July	18.55	dcni	5.93	dcni	dcni	dcni	dcni	8720	3.53	0.21	30.78	1.83	16660	2.50	0.06	41.65	1.00
Aug	23.93	767.66[c]	5.73	0.19	0.15	0.14	0.11	16100	0.70	0.16	9.07	2.26	27680	1.00	0.17	27.68	4.71
Sept	13.20	1678.62	5.62	0.28	0.22	0.41	0.33	10300	2.23	0.28	22.97	2.88	20100	0.17	0.26	3.42	5.23
Oct	20.31	1529.83	5.65	0.23	0.25	0.35	0.38	11000	0.75	0.19	8.25	2.09	25100	0.84	0.21	21.08	5.27
Nov	1.96	17.13	5.36	0.26	0.21	trace[e]	trace	1590	1.06	0.20	1.69	0.32	2720	1.35	0.20	3.67	0.56
Dec	3.56	1.95	5.29	nsnf[d]	nsnf	nsnf	nsnf	690	4.85	0.11	3.35	0.08	631	1.51	0.14	0.98	0.09
1974																	
Jan	6.02	265.26	5.31	0.96	bmdl[f]	0.25	bmdl	2670	5.86	0.11	15.59	0.29	3670	1.67	0.08	5.79	0.28
Feb	1.50	0.79	5.22	nsnf	nsnf	nsnf	nsnf	470	0.20	0.08	0.09	0.06	766	0.73	0.15	0.56	0.11
Mar	2.77	0.00	5.14	0.00	0.00	0.00	0.00	2770	5.20	0.21	14.40	0.58	1780	3.31	bmdl	5.89	bmdl
Apr	5.59	0.00	5.11	0.00	0.00	0.00	0.00	480	0.33	bmdl	0.16	bmdl	1480	0.48	bmdl	0.71	bmdl
May	10.27	269.66	5.20	0.57	bmdl	0.16	bmdl	2720	6.60	0.19	17.95	0.52	2710	2.76	0.10	7.48	0.27
June	36.07	1957.27	5.50	0.80	bmdl	1.57	bmdl	12540	7.35	0.16	92.17	2.01	28620	4.08	0.10	116.77	2.86
July	22.37	1988.88	5.71	0.23	0.49	0.46	0.97	12730	3.25	0.13	41.37	1.65	29970	1.61	0.36	48.25	10.19
Aug	16.26	1090.20	5.66	0.26	bmdl	0.25	bmdl	7890	0.38	0.09	3.00	0.71	17010	0.08	0.17	1.36	2.89
Sept	11.70	683.69	5.43	0.09	bmdl	0.06	bmdl	3210	0.40	0.27	1.28	0.87	5640	0.22	0.16	1.26	0.79
Oct	8.96	688.12	5.50	0.26	bmdl	0.15	bmdl	6300	4.28	0.23	26.96	1.45	12560	2.16	0.17	27.13	2.16
Nov	2.53	5.29	5.26	0.14	bmdl	trace	bmdl	590	0.78	0.08	0.46	0.05	1000	0.08	0.07	0.09	0.08
Dec	4.73	75.35	5.36	1.26	bmdl	0.09	bmdl	900	1.03	0.23	0.93	0.21	3480	0.50	0.11	1.70	0.37
1975																	
Jan	1.21	0.00	5.25	nsnf	nsnf	nsnf	nsnf	970	0.50	0.20	0.49	0.19	1030	0.11	0.11	0.11	0.11
Feb	9.97	[illegible]	5.30	1.76	bmdl	0.69	bmdl	3710	1.67	0.06	6.20	0.22	5720	1.03	bmdl	5.89	bmdl
Mar	4.20	117.67	5.39	3.72	bmdl	0.44	bmdl	3060	1.29	bmdl	3.93	bmdl	3500	0.60	bmdl	2.10	bmdl
Apr	4.09	88.63	5.27	3.60	bmdl	0.30	bmdl	1560	1.30	bmdl	2.15	bmdl	1110	0.13	bmdl	0.14	bmdl
May	26.31	1637.96	5.45	3.46	bmdl	4.98	bmdl	7650	1.22	bmdl	9.38	bmdl	16850	0.14	bmdl	2.36	bmdl
June	11.45	631.40	5.49	3.60	0.35	1.55	0.15	6730	1.70	bmdl	11.46	bmdl	10330	0.56	bmdl	5.78	bmdl
July	9.00	217.32	5.38	2.00	bmdl	0.43	bmdl	2760	1.16	bmdl	3.20	bmdl	4230	0.07	bmdl	0.30	bmdl
Aug	8.18	167.16	5.32	1.80	bmdl	0.30	bmdl	1730	1.48	bmdl	2.56	bmdl	3180	0.20	bmdl	0.64	bmdl
Sept	26.77	1007.36	5.53	2.22	bmdl	2.26	bmdl	8640	5.05	0.11	43.63	0.95	18280	0.06	bmdl	1.09	bmdl
Oct	5.63	318.31	5.52	2.46	bmdl	0.78	bmdl	6630	4.81	0.09	30.93	0.58	9920	2.02	bmdl	20.04	bmdl
Nov	7.67	421.92	5.40	1.37	bmdl	0.58	bmdl	3370	1.86	bmdl	6.20	bmdl	5200	1.36	bmdl	7.07	bmdl
Dec	3.09	7.36	5.34	1.36	bmdl	0.01	bmdl	1730	1.06	bmdl	1.80	bmdl	1830	0.53	bmdl	0.97	bmdl

a dcni, control drain line was not installed until the middle of August.

b pcnd, PO_4-P was not determined on these samples.

c This value represents only one half the month.

d nsnf, no sample was taken due to negligible flow.

e trace, discharge values were less than 0.01 kg of NO_3-N and PO_4-P.

f bmdl, concentration was below the minimum detection level. Minimum detection levels for NO_3-N and PO_4-P are 0.04 ppm and 0.06 ppm, respectively. Discharge values for concentration lower than these levels were not calculated.

Table 13. Total annual quantities of rainfall, irrigation, drainage, surface runoff, estimated evapotranspiration, NO_3-N discharged in drainage and runoff, and PO_4-P discharged in drainage and runoff for ST, DT and DTL soil management plots during 1973, 1974 and 1975.

	1973			1974			1975		
	ST	DT	DTL	ST	DT	DTL	ST	DT	DTL
Rainfall (cm)	134.64	134.64	134.64	124.85	124.85	124.85	116.37	116.37	116.37
Irrigation (cm)	20.58	20.58	20.58	38.66	38.66	38.66	29.66	29.66	29.66
Rainfall + Irrigation (cm)	155.22	155.22	155.22	163.51	163.51	163.51	146.03	146.03	146.03
Drainage (cm)	83.31	58.50	29.69	84.95	43.83	30.61	64.72	26.46	19.49
Surface Runoff (cm)	0.30	9.90	12.20	0.17	9.68	8.89	0.23	4.42	6.60
Drainage + Runoff (cm)	83.61	68.40	41.89	85.12	53.51	39.50	64.95	30.88	26.09
Estimated Evapotranspiration* (cm)	71.61	86.82	113.33	78.39	110.00	124.01	81.08	115.15	119.94
NO_3-N discharged in drainage (kg/ha)	31.75	10.36	7.97	35.30	3.74	13.34	45.77	0.36	3.65
NO_3-N discharged in runoff (kg/ha)	0.02	0.32	1.16	< 0.01	0.69	0.82	0.02	0.25	0.44
Total NO_3-N discharged (kg/ha)	31.77	10.68	9.13	35.31	4.43	14.16	45.79	0.61	4.09
Percentage NO_3-N discharged (%)	18.74	6.30	5.38	20.82	2.61	8.35	27.01	0.36	2.41
PO_4-P discharged in drainage (kg/ha)	3.75	0.68	0.33	3.14	0.70	0.86	2.47	0.01	0.04
PO_4-P discharged in runoff (kg/ha)	< .01	0.10	0.16	< 0.01	0.37	0.32	0.01	0.15	0.23
Total PO_4-P discharged (kg/ha)	3.76	0.78	0.49	3.15	1.07	1.18	2.48	0.16	0.27
Percentage PO_4-P discharged (%)	20.29	4.22	2.66	16.99	5.79	6.38	13.42	0.86	1.46

*Evapotranspiration was calculated by subtracting total quantities of drainage and surface runoff from the total quantities of rainfall and irrigation. The water balance components of deep seepage and soil water storage were assumed negligibly small and were thus ignored for these calculations.

Table 14: Total annual quantities of rainfall, irrigation, drainage, estimated evapotranspiration, NO_3-N discharged in drainage, and PO_4-P discharged in drainage for the Control soil management plot during 1973-1975.

	1973	1974	1975
Rainfall (cm)	134.64	124.85	116.37
Irrigation (cm)	0	0	0
Rainfall plus irrigation (cm)	134.64	124.85	116.37
Drainage (cm)	37.75	66.05	46.03
Estimated Evapotranspiration* (cm)	117.47	97.46	100.00
NO_3-N discharged (kg/ha)	0.90	2.95	12.30
Percentage NO_3-N discharged (%)	0.53	1.74	7.26
PO_4-P discharged (kg/ha)	0.82	0.97	0.51
Percentage PO_4-P discharged (%)	4.44	5.25	0.81

*Evapotranspiration was calculated by subtracting total quantities of drainage from the total quantities of rainfall. The water balance components of deep seepage, surface runoff, and soil water storage were assumed negligibly small and were thus ignored for these calculations.

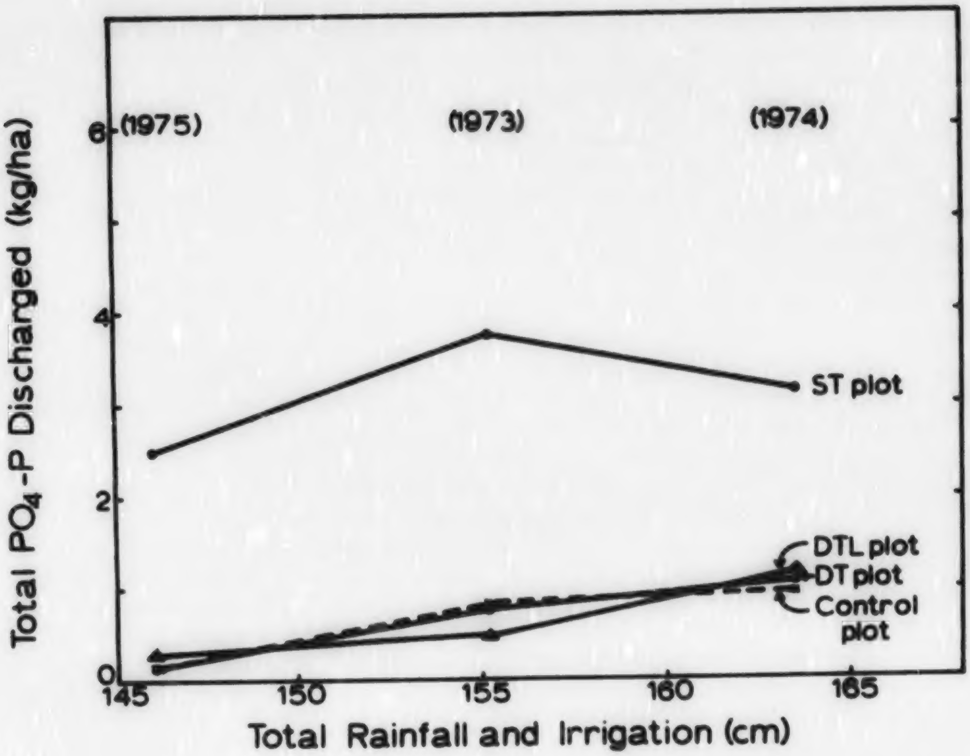


FIGURE 11. Total PO_4-P discharged annually with surface and subsurface drainage water versus total amounts of rainfall plus irrigation for ST, DT, DTL, and Control soil management plots for the period 1973-1975.

plot except for the 1974 data when the NO_3-N discharge decreased. Magnitudes were generally similar for NO_3-N and PO_4-P losses from the deep-tilled plots. Discharge of NO_3-N decreased slightly with increasing rainfall plus irrigation for ST, but discharges of PO_4-P increased slightly with increasing rainfall plus irrigation. Nitrate losses were always many-fold greater for ST than either DT or DTL plots. Discharge of PO_4-P from the Control plot (Table 14) generally had the same magnitude as that for the deep-tilled plots. Losses of nitrate, from the Control, however, were greater than DT or DTL in 1975 but were considerably less during 1973 and 1974.

Expressing the annual losses of NO_3-N in both surface and subsurface drainage as percentages of N applied, NO_3-N discharged from the ST plot accounted (Table 13) for 18.74% in 1973, 20.82% in 1974, and 27.01% in 1975. For DTL comparable values were 5.38% in 1973, 8.35% in 1974, and 2.41% in 1975. Comparable values for DT were 6.30% in 1973, 2.61% in 1974, and 0.36% in 1975. Thus average losses of NO_3-N over the 3-year period were 22.2% for ST, 5.4% for DTL, and 3.1% for DT. These values are less than the values of 31.9% for ST, 15.0% for DTL, and 8.3% for DT obtained during 1971-1972 by Calvert (1975). For a six-month period during 1971, Calvert and Phung (1971) obtained % N losses of 35.4% for ST, 16 7% for DTL, and 8.7% for DT. Higher N losses obtained during 1971 and 1972 than during 1973-1975 may be partially due to less uptake of N by the smaller and younger citrus trees. Calvert and Phung (1971) attributed the greater N loss from DTL relative to that from DT to greater rates of nitrification due to the beneficial effect of lime on soil microorganisms.

Annual losses of PO_4-P with surface and subsurface drainage during 1973, 1974, and 1975 were 3.76, 3.15, and 2.48% for ST; 0.49, 1.18, and 0.27% for DTL; and 0.78, 1.07, and 0.16% for DT. Thus average losses of PO_4-P over the 3-year period were 3.13% for ST, 0.65% for DTL, and 0.67% for DT. These percentages are in the same order of magnitude but less than the values of 14.2% for ST, 2.0% for DTL, and 3.4% for DT obtained during 1971-1972 by Calvert (1975). The unfertilized Control plot produced PO_4-P losses which were of the same order as the fertilized DT or DTL treatments in all three years of the study.

Percentage losses of NO_3-N and PO_4-P in the Central Sump (sampling site 7)and South Sump (sampling site 8) outflow water was calculated based on the amount of fertilizer applied to the nine citrus plots (9 ha) comprising the entire SWAP citrus grove in each of the three years in the study (Table 15). In 1973 losses of NO_3-N from the Central and South Sumps both approximated 10.4% of that applied to the nine citrus plots. Loss of PO_4-P was calculated to be 5.7% from the Central Sump and 10.1% from the South Sump in 1973. The 1974 data show that NO_3-N percentage losses from the Central Sump and the South Sump were very close with 14.0% lost from the Central Sump and 14.2% lost from the South Sump. Approximately 5.0% of the PO_4-P was accounted for as a loss from the Central Sump in 1974 and 12.0% was calculated to be lost from the South Sump in 1974. In 1975 loss of NO_3-N and PO_4-P was much less with only 8.0% of the NO_3-N appearing at the Central Sump and only 3.0% accounted for at the South Sump. PO_4-P losses amounted to only 1.2% at the Central Sump and 0.07% at the South Sump in 1975.

Table 15: Total annual quantities of rainfall plus irrigation, water, NO_3-N, and PO_4-P discharged from the Central Sump and South Sump of the SWAP citrus grove during 1973, 1974, and 1975.

	1973		1974		1975	
	Central Sump	South Sump	Central Sump	South Sump	Central Sump	South Sump
Rainfall plus Irrigation (M^3/ha x 10^2)	155.22	155.22	163.51	163.51	146.03	146.03
Water discharged (M^3/ha x 10^2)	649.50	1,249.11	532.70	1,084.66	485.40	811.00
NO_3-N discharged (kg/ha)	158.38	158.22	214.36	216.95	122.13	46.49
PO_4-N discharged (kg/ha)	9.46	16.84	8.38	19.98	1.94	0.11

During 1973 and 1974 the amount of NO_3-N lost in the Central Sump water was approximately the same as the amount lost from the South Sump. Furthermore, the concentration of NO_3-N in the Central Sump was approximately twice that in the South Sump while the amount of flow from the South Sump was about twice that from the Central Sump, thus accounting for the almost equal losses of NO_3-N from both sites. Without more intensive investigation, it is not possible to say whether these figures are merely coincidences or whether the bulk of the NO_3-N showing up at the South Sump was in fact the same NO_3-N which originated at the Central Sump. Furthermore, in 1975, a year of reduced drainage flow, the amount of NO_3-N lost from the Central Sump approximated 8.0% as compared to only 3.0% loss of NO_3-N from the South Sump. This difference might be explained by the fact that the water was recycled for irrigation use more in this drier year, and because of fewer rainfall events the water remained in the perimeter ditch system for the grove much longer before flowing out and, therefore, considerably more time was available for denitrification to occur and the chance that NO_3-N was absorbed by ditch vegetation was considerably greater.

The percentage loss of PO_4-P was about twice as high from the South Sump as from the Central Sump in 1973 and 1974, but in 1975 losses from both Sumps were almost nil (only 1.2% from the Central Sump and 0.07% from the South Sump). The same reasons given for reduced loss of NO_3-N in 1975 also apply here. In 1975, there was a much greater chance for PO_4-P to be removed in the perimeter ditch system in both biological and chemical sinks which fix PO_4-P.

As stated earlier, it is not known for certain whether the close correspondence of losses of NO_3-N from the Central and South Sumps in 1973 and 1974 is coincidental or not, but it is presumed that the balance of nutrients in the perimeter ditch system surrounding the SWAP area is fairly complex. That is, the PO_4-P and NO_3-N concentration and discharge at the South Sump is an integrated summation of inputs, such as subsurface drains, surface runoff from the plot areas, surface runoff from the non-agricultural area (largely vacant land) seepage from this area and from adjoining areas into the ditch system, fixation of NO_3-N in rainfall from thunderstorms and nutrient content of irrigation water. Both well water and water brought in from the North Saint Lucie River Water Management District are used for irrigation of the SWAP experimental grove. These are only a few of the possible reasons for observed increases as well as decreases in nutrient concentrations between the Central Sump and the South Sump in the SWAP experimental grove. All of these possibilities should be investigated before an exact nutrient balance at this location can be obtained. However, a loss of approximately 10% of the NO_3-N applied as fertilizer would not be considered an excessive loss, especially when it is possible that part of the NO_3-N originated from sources other than applied fertilizer.

Monthly values of subsurface drainage were found to be linearly related (Figs. 12, 13, and 14) with monthly totals of rainfall plus irrigation for the 3-year period for each soil treatment. Linear regression equations (Table 16) were least-square fitted to the data for the three treatments. The slopes of these equations were 0.70, 0.35, and 0.25 for ST, DT, and DTL plots, respectively. These slopes show that for a given monthly input

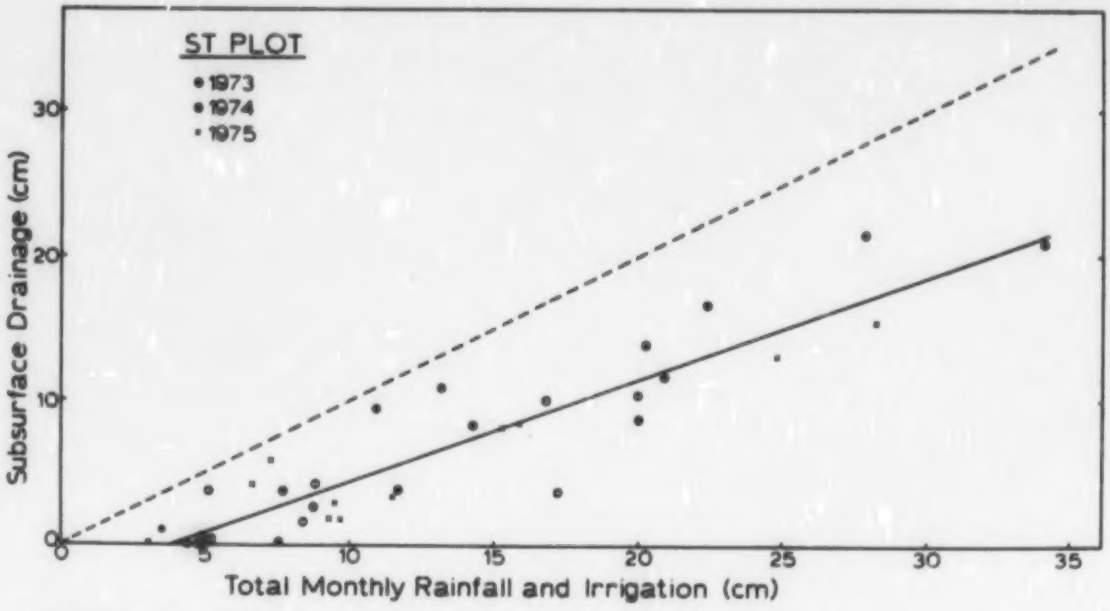


FIGURE 12. Monthly amounts of subsurface drainage plotted versus amounts of rainfall plus irrigation for the ST soil treatment during the period 1973-1975. The dotted line has a zero intercept and a unit slope, and the solid line was obtained using linear regression. The regression equation is presented in Table 16.

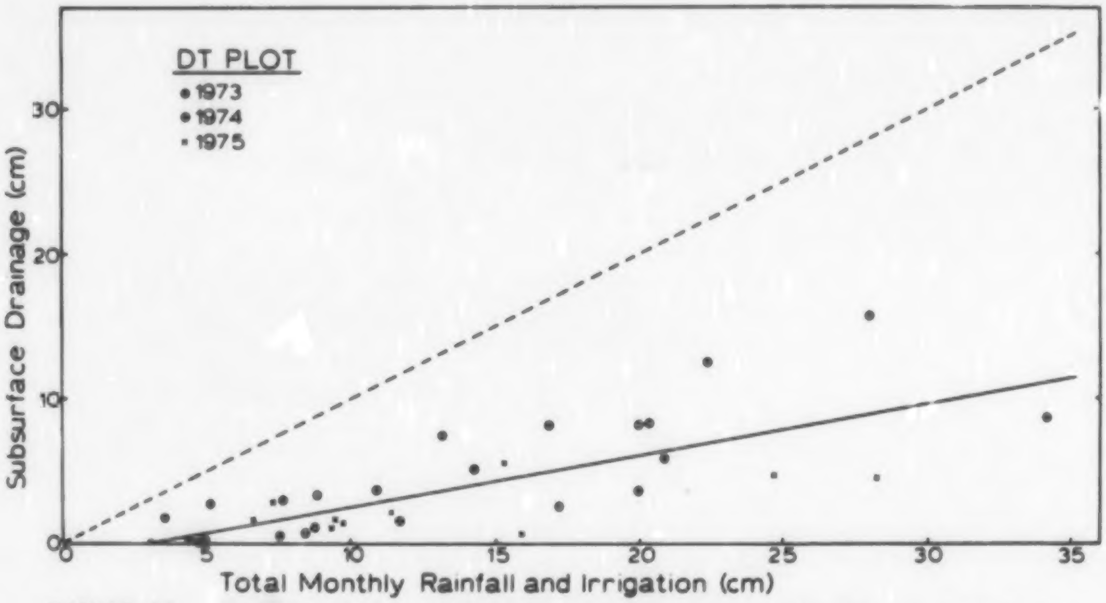


FIGURE 13. Monthly amounts of subsurface drainage plotted versus rainfall plus irrigation for the DT plot during the period 1973-1975. The dotted line has a zero intercept and a unit slope, and the solid line was obtained using linear regression. The regression equation is presented in Table 16.

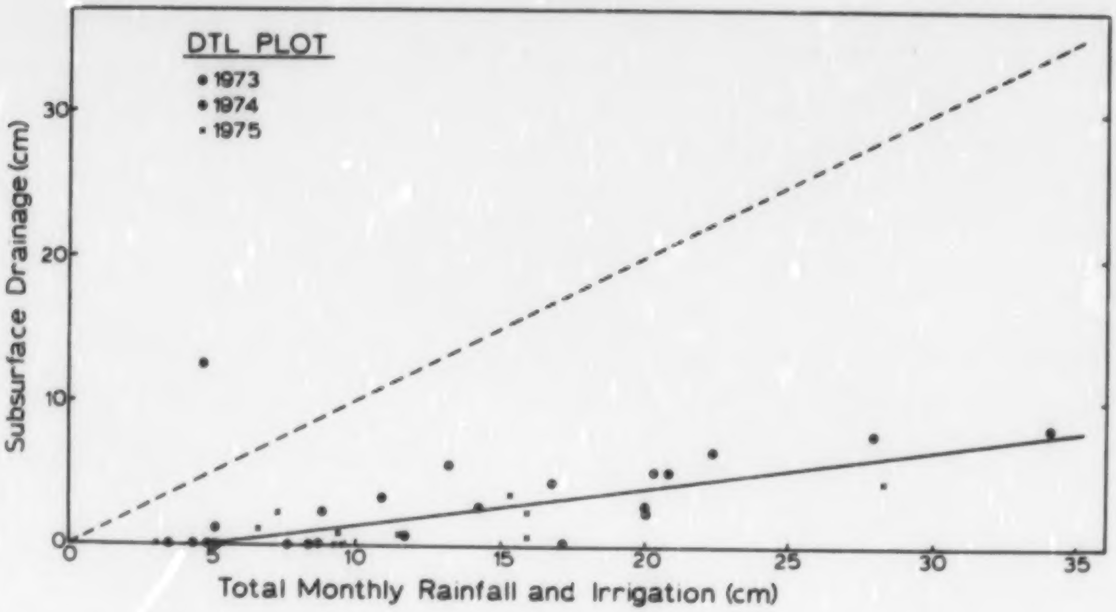


FIGURE 14. Monthly amounts of subsurface drainage plotted versus rainfall plus irrigation for the DTL plot during the period 1973-1975. The dotted line has a zero intercept and a unit slope, and the solid line was obtained using linear regression. The regression equation is presented in Table 16.

Table 16: Linear regression equations relating D, monthly subsurface drainage (cm), and I, monthly rainfall plus irrigation (cm), for ST, DT and DTL plots for the period 1973, 1974 and 1975.

Soil Treatment		R-Square* (%)	C.V.** (%)	I_o*** (cm)
ST	D = -2.65 + 0.70 I	85.68	36.05	3.8
DT	D = -0.96 + 0.35 I	57.39	68.03	2.7
DTL	D = 1.05 + 0.25 I	72.63	56.38	4.1

*R-Square is the regression coefficient squared.

**CV is the coefficient of variation.

***I_o is the value of I corresponding to D = 0.

of rainfall plus irrigation, the amount of monthly drainage from ST was approximately twice that for DT. Drainage from DTL was slightly less than from DT. These findings confirm drainage results presented earlier in this report.

Estimates of N, P, and K removal in oranges are presented in Table 17 for the 3 soil treatments. Using average fruit yields from 1975 and nutrient contents of fruit by Reitz (1961), N removal was calculated to be 29.9, 28.0, and 38.7 kg/ha for ST, DT, and DTL plots. Removal of P was calculated to be 3.8, 3.5, and 4.9 kg/ha for ST, DT, and DTL. Expressing these nutrient removals as percentages of fertilizer applied (169.52 kg/ha of N and 18.48 kg/ha of P), N removal by fruit in ST, DT and DTL plots was 20.6, 18.9, and 26.5%. Thus the sums of the percentages of N discharged with surface and subsurface drainage and N removed with fruit for ST, DT and DTL plots are 39.8, 19.6, and 28.2%. Comparable percentages for P were 23.7, 19.6, and 27.2% for ST, DT, and DTL. These values indicate that large percentages of the applied N and P are unaccounted for, i.e. greater than 60% for N and greater than 70% for P. Individual values are 60.2, 80.4, and 71.8% of the applied N for ST, DT, and DTL, and 76.3, 80.4, and 72.8% of the applied P for ST, DT, and DTL. The percentage of unrecovered N and P seems to be highest in the DT plot. The unrecovered N was probably distributed among uptake by the citrus tree and sod, denitrification of NO_3-N to the gaseous state, adsorption of NH_4-N to the soil

Table 17: Average fruit yields of Pineapple Orange growing in ST, DT, and DTL treatment plots during 1975-1976 and calculated amounts of N, P, and K in the harvested fruit. Calculations were based upon the publication of Reitz (1961) who stated that 1000 boxes (90 lbs per box) of oranges contain 179.20 kg of N, 22.48 kg of P, and 269.62 kg of K.

Soil Treatment	Fruit Yield (boxes/ha)	N Removal (kg/ha)	P Removal (kg/ha)	K Removal (kg/ha)
ST	167	29.9	3.8	45.0
DT	156	28.0	3.5	42.1
DTL	216	38.7	4.9	58.2

colloids, precipitation as iron and aluminum phosphates, and P in the soil solution. The relatively large percentages of N and P not recovered as surface and subsurface drainage loss and removal by citrus fruit seem to suggest that the content of these nutrients in the soil at any given time may be rather large. The exact fate of the unrecovered N and P can not be determined at this time.

Intensive Studies Of Nutrient Leaching

Four short-term, intensive studies on NO_3-N and PO_4-P discharge losses in both surface and subsurface drainage water from ST, DT, and DTL tillage systems were conducted in March and May of 1974, and in February and March of 1975. These studies were conducted during the drier months of these years so that the water input (irrigation) could be controlled more precisely. Losses were examined over 14-day intervals that followed irrigations of 16.0, 8.2, 5.7 and 2.4 cm of water. Fertilizer amounting to 530 kg per ha of an 8-2-8 mixture (42 kg/ha nitrogen as ammonium and nitrate and 50 kg/ha PO_4-P as super-phosphate) was applied immediately before turning on the irrigation system. An exception was the 5.7 cm irrigation period (February 1975) when plots were not fertilized prior to irrigation. Instead, the preceding fertilization was made three months prior to the 5.7 cm irrigation.

Concentration, nutrient flux and water flow curves for the four events are presented in Figs. 15 through 26 for ST, DT, and DTL plots. Tables 18 through 21 present the same data in numerical form along with values for water table height, rainfall and time. A summary table composed of means for each event is presented in Table 22.

A series of smooth NO_3-N and PO_4-P concentration and discharge curves with well defined peaks were obtained from these intensive studies. Examples of the type of curves obtained by intensive sampling are presented as Figs. 15, 16, and 17 for subsurface drainage water from ST, DT, and DTL plots during parts of May and June of 1974 (16.0 cm of irrigation was applied on May 21, 1974).

Surface-tilled plots gave greater NO_3-N discharges (Table 22), 14.4 kg/ha NO_3-N, in the 14-day period after the 16.0 cm irrigation, than either DT or DTL, which were 0.6 and 5.1 kg/ha NO_3-N, respectively. Following the 16-cm irrigation, maximum concentrations of NO_3-N in the subsurface drainage of both ST and DTL were much higher (18.4 and 16.8 μg/ml) than of DT (2.3 μg/ml). For the 16.0 cm irrigation concentrations of NO_3-N in drainage from the ST and DTL plots reached two peaks, one at 2 days and another at 13 days (Figs. 15 and 17); however, only one peak at 2 days was observed for the DT plot. Nutrient discharges from ST were usually greater than from DTL mainly because water discharge was greater. Although subsurface drainage from the DT plot exceeded that from DTL, NO_3-N discharges from DTL were higher than from DT, probably because the mixed and limed soil had a higher nitrification rate, (Phung, 1971). ST plots discharged up to 0.38 kg/ha PO_4-P in the 14-day period following the 16.0 cm irrigation, but phosphate discharges from DT and DTL were only 0.07 to 0.11 kg/ha PO_4-P in the 14-day period, respectively.

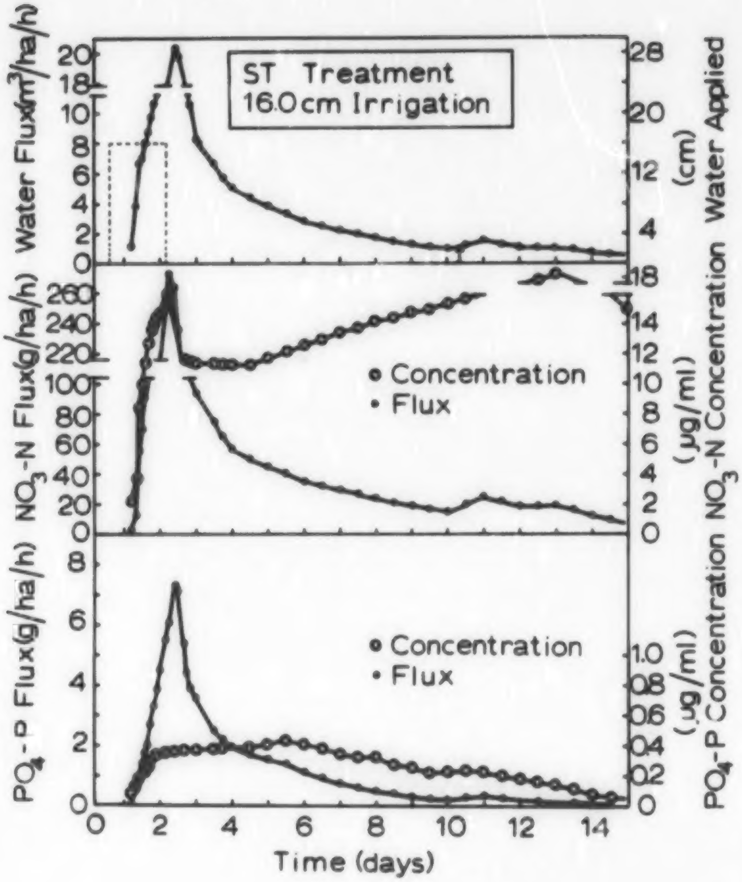


FIGURE 15. Fluxes of drainage water, NO_3-N, and PO_4-P and concentrations of NO_3-N and PO_4-P in subsurface drainage from the ST soil management treatment during a 14-day period (March 6-19, 1974) following 16.0-cm irrigation. Water was applied continuously over a 39-hour period immediately after a quarterly application of 530 kg/ha of an 8-2-8 fertilizer. Rainfall occurred on days 9 and 10 for a total of 2.4 cm.

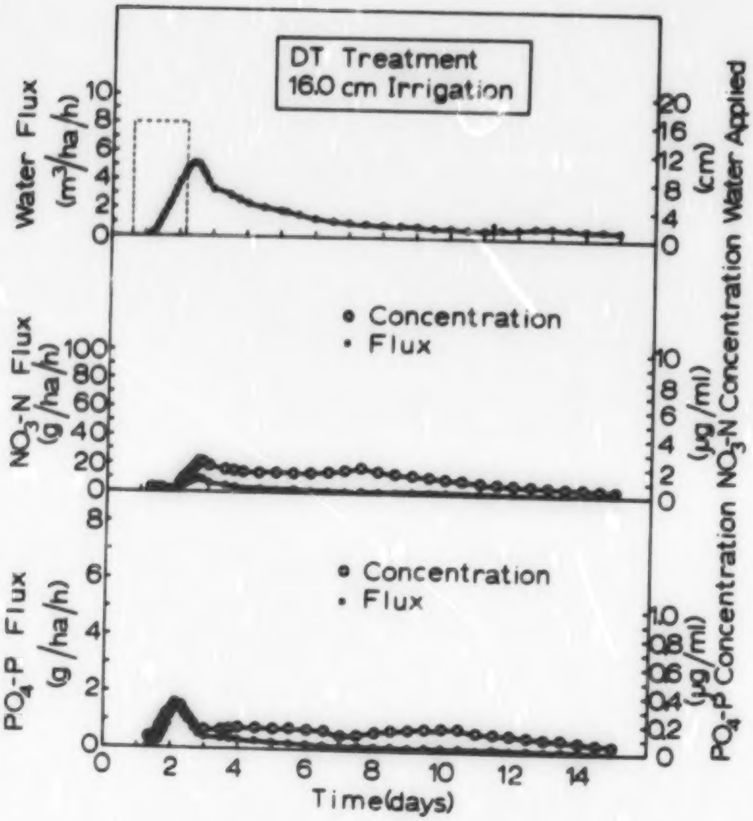


FIGURE 16. Fluxes of drainage water, NO_3-N and PO_4-P and concentrations of NO_3-N and PO_4-P in subsurface drainage from the DT soil management treatment during a 14-day period (March 6-19, 1974) following a 16.0-cm irrigation. Water was applied continuously over a 39-hour period immediately after a quarterly application of 530 kg/ha of an 8-2-8 fertilizer. Rainfall occurred on days 9 and 10 for total of 2.4 cm.

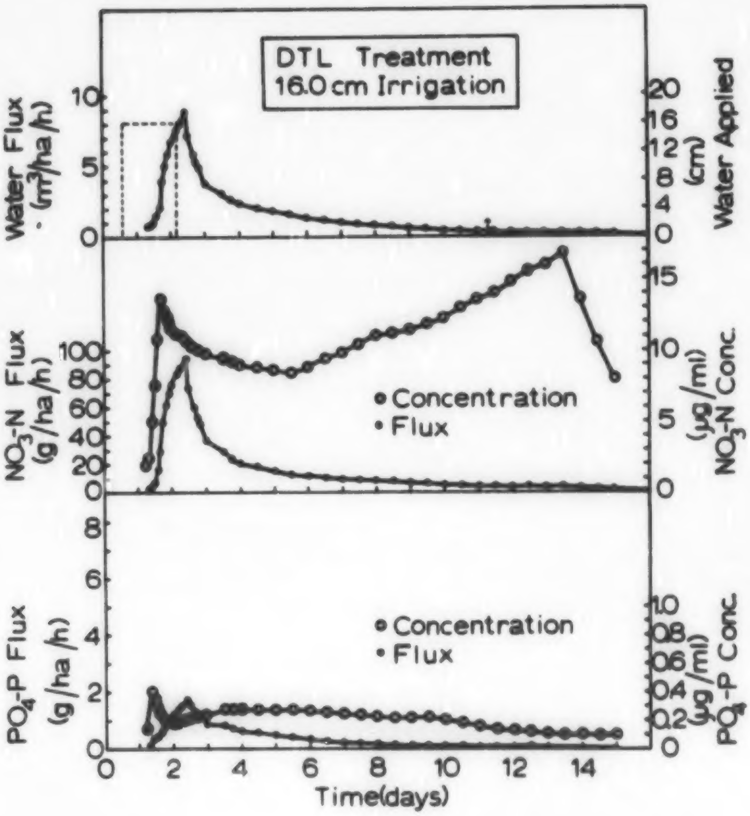


FIGURE 17. Fluxes of drainage water, NO_3-N and PO_4-P and concentrations of NO_3-N and PO_4-P in subsurface drainage from the DTL soil management treatment during a 14-day period (March 6-19, 1974) following a 16.0-cm irrigation. Water was applied continuously over a 39-hour period immediately after a quarterly application of 530 kg/ha of an 8-2-8 fertilizer. Rainfall occurred on days 9 and 10 for a total of 2.4 cm.

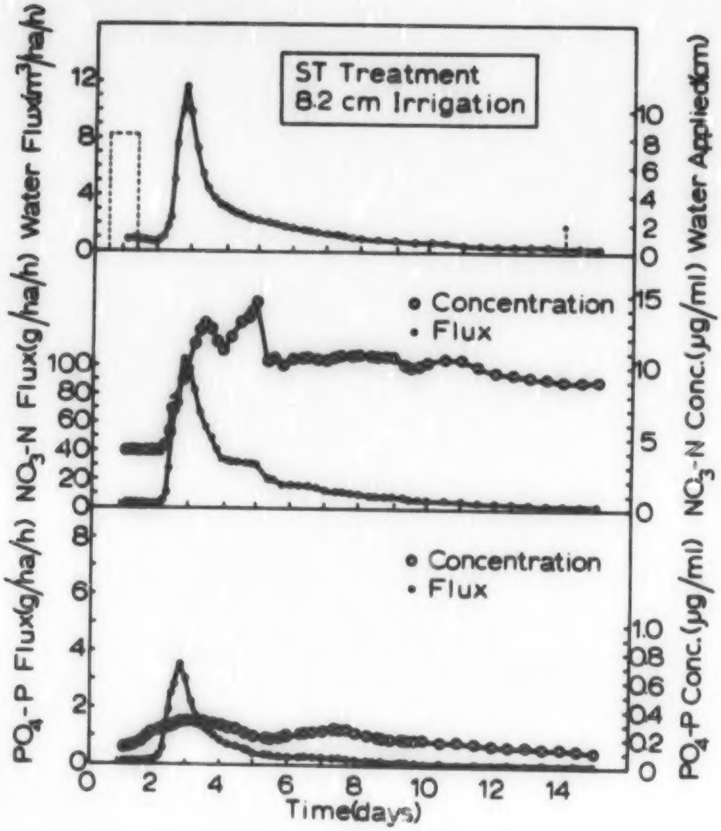


FIGURE 18. Fluxes of drainage water, NO_3-N and PO_4-P and concentrations of NO_3-N and PO_4-P in subsurface drainage from the ST soil management treatment during a 14-day period (May 21 through June 3, 1974) following a 8.2-cm irrigation. Water was applied continuously over a 20-hour period immediately after a quarterly application of 530 kg/ha of an 8-2-8 fertilizer. Rainfall occurred on days 13 and 14 for a total of 2.7 cm.

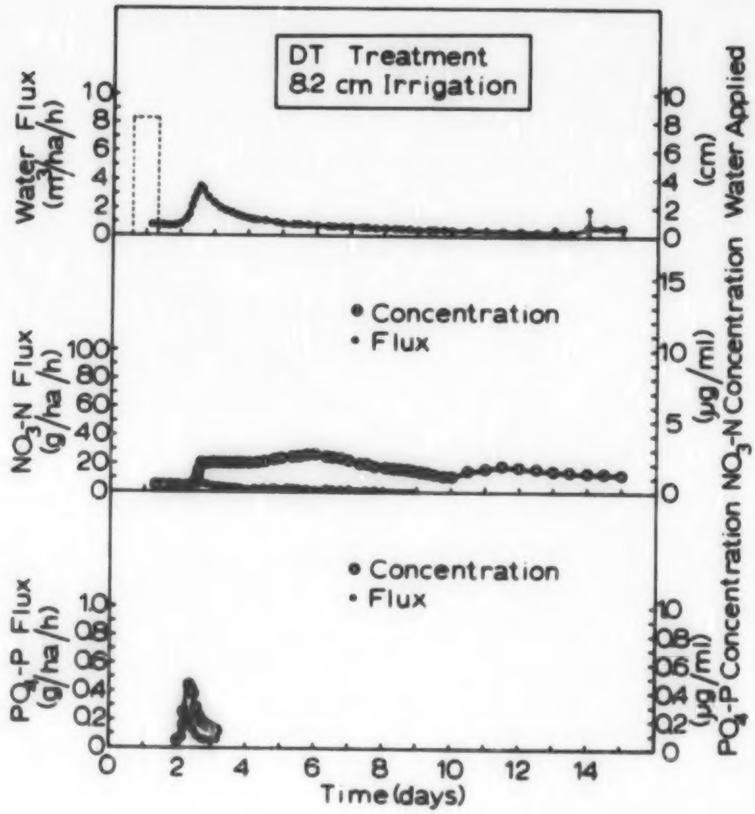


FIGURE 19. Fluxes of drainage water, NO_3-N and PO_4-P and concentrations of NO_3-N and PO_4-P in subsurface drainage from the DT soil management treatment during a 14-day period (May 21 through June 3, 1974) following a 8.2-cm irrigation. Water was applied continuously over a 20-hour period immediately after a quarterly application of 530 kg/ha of an 8-2-8 fertilizer. Rainfall occurred on days 13 and 14 for a total of 2.7 cm.

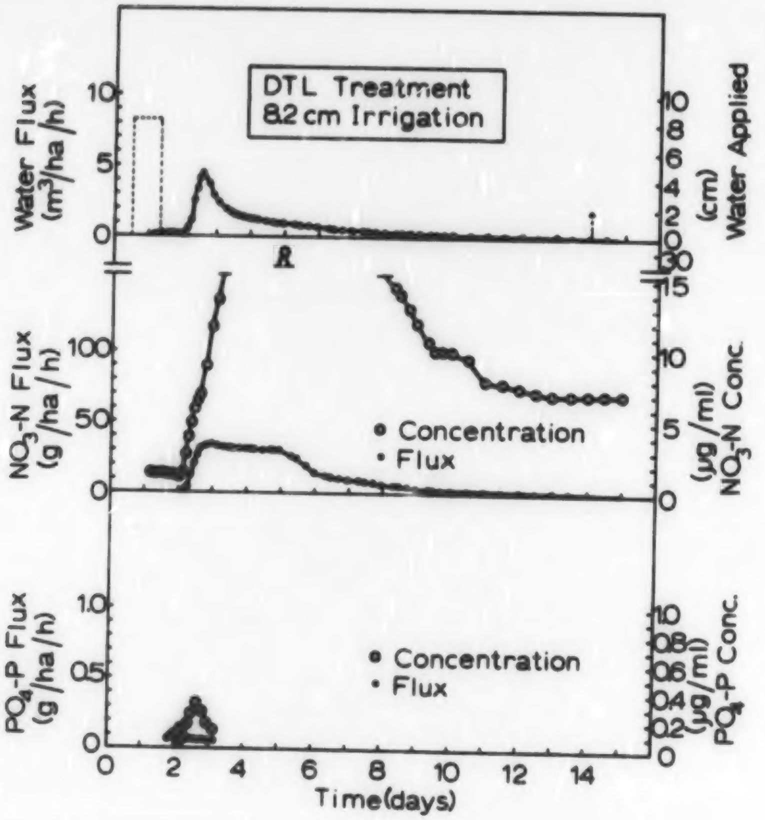


FIGURE 20. Fluxes of drainage water, NO_3-N and PO_4-P and concentrations of NO_3-N and PO_4-P in subsurface drainage from the DTL soil management treatment during a 14-day period (May 21 through June 3, 1974) following a 8.2-cm irrigation. Water was applied continuously over a 20-hour period immediately after a quarterly application of 530 kg/ha of an 8-2-8 fertilizer. Rainfall occurred on days 13 and 14 for a total of 2.7 cm.

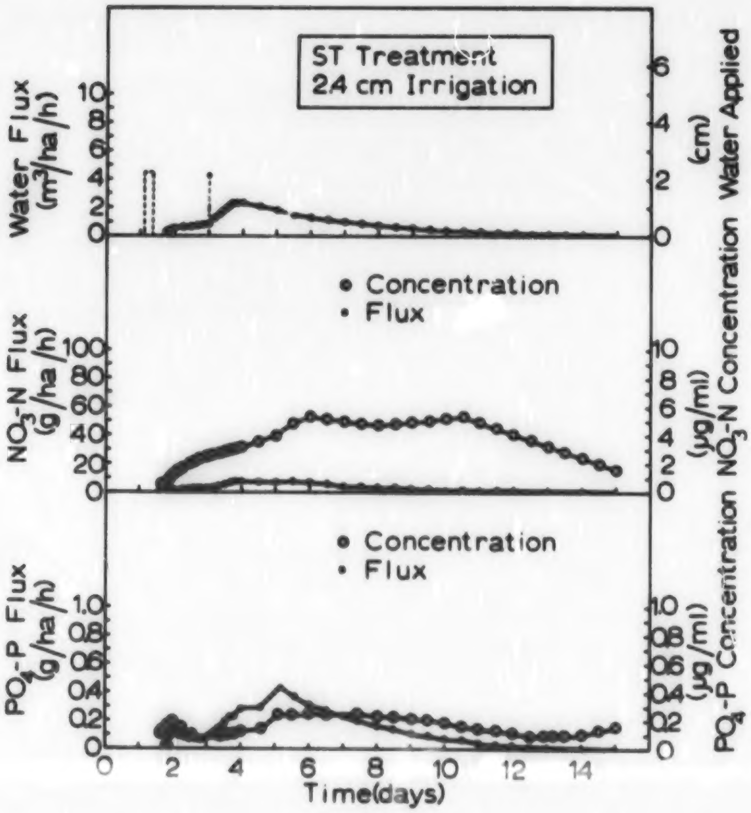


FIGURE 21. Fluxes of drainage water, NO_3-N and PO_4-P and concentrations of NO_3-N and PO_4-P in subsurface drainage from the ST soil management treatment during a 14-day period (March 17-30, 1975) following a 2.4-cm irrigation. Water was applied continuously over a 6-hour period immediately after a quarterly application of 530 kg/ha of an 8-2-8 fertilizer. Rainfall occurred on days 2 and 3 for a total of 2.9 cm.

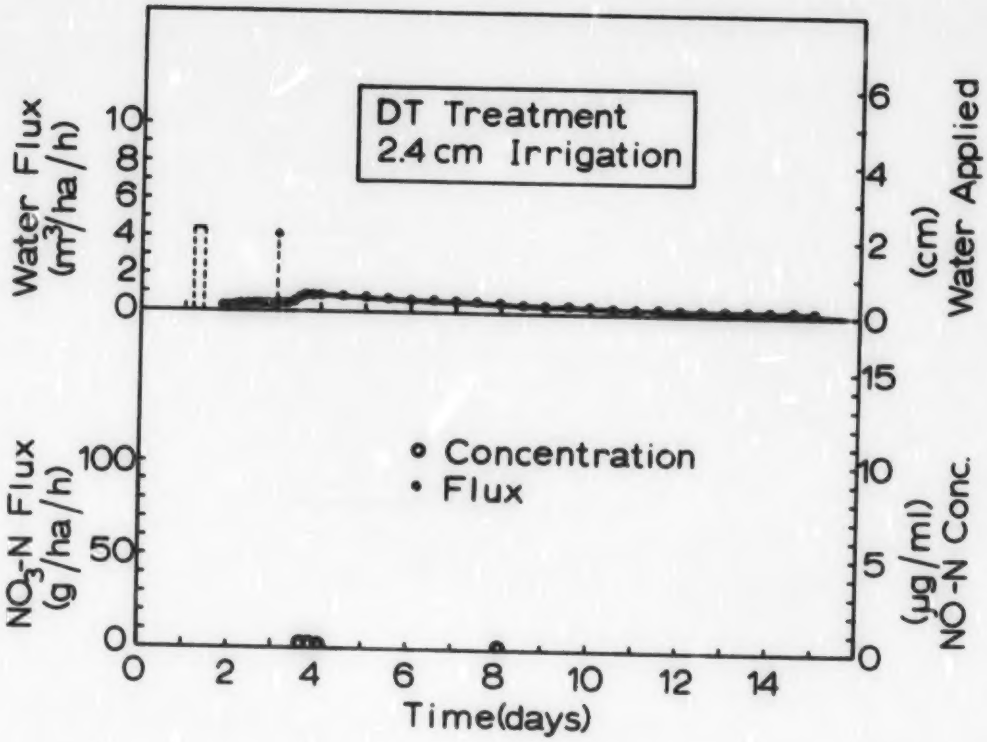


FIGURE 22. Fluxes in drainage water and NO_3-N and concentrations of NO_3-N in subsurface drainage from the DT soil management treatment during a 14-day period (March 17-30, 1975) following a 2.4-cm irrigation. Water was applied continuously over a 6-hour period immediately after a quarterly application of 530 kg/ha of an 8-2-8 fertilizer. Rainfall occurred on days 2 and 3 for a total of 2.9 cm. Concentrations of fluxes of PO_4-P were very small and are not shown on the figure.

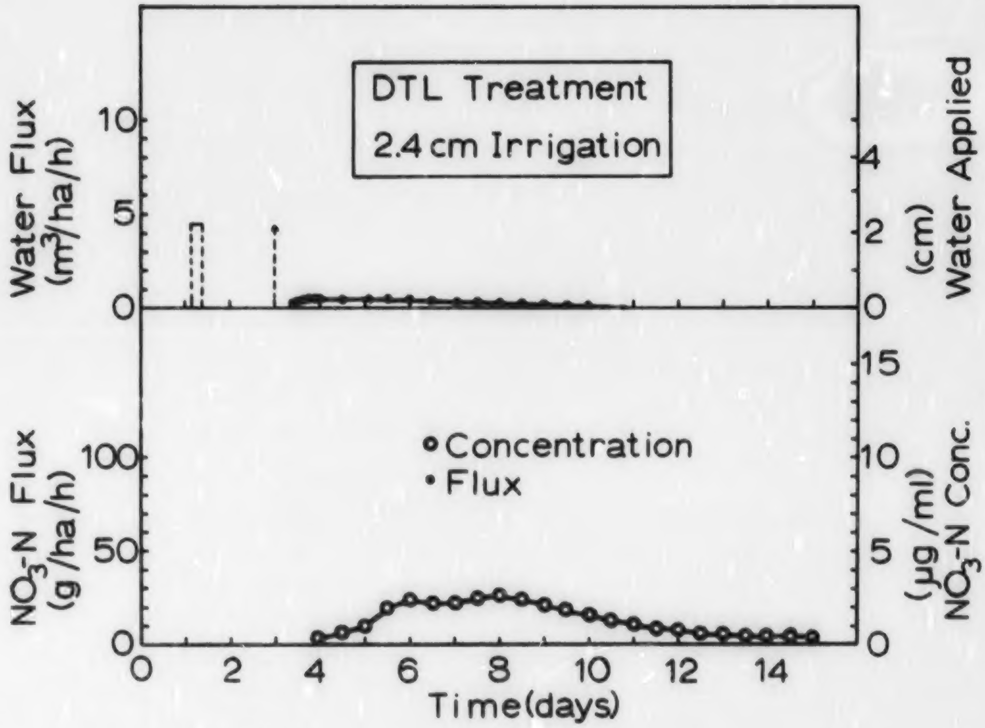


FIGURE 23. Fluxes of drainage water and NO_3-N and concentrations of NO_3-N in subsurface drainage from the DTL soil management treatment during a 14-day period (March 17-30, 1975) following a 2.4-cm irrigation. Water was applied continuously over a 6-hour period immediately after a quarterly application of 530 kg/ha of an 8-2-8 fertilizer. Rainfall occurred on days 2 and 3 for a total of 2.9 cm. Concentrations and fluxes of PO_4-P were very small and are not shown on the figure.

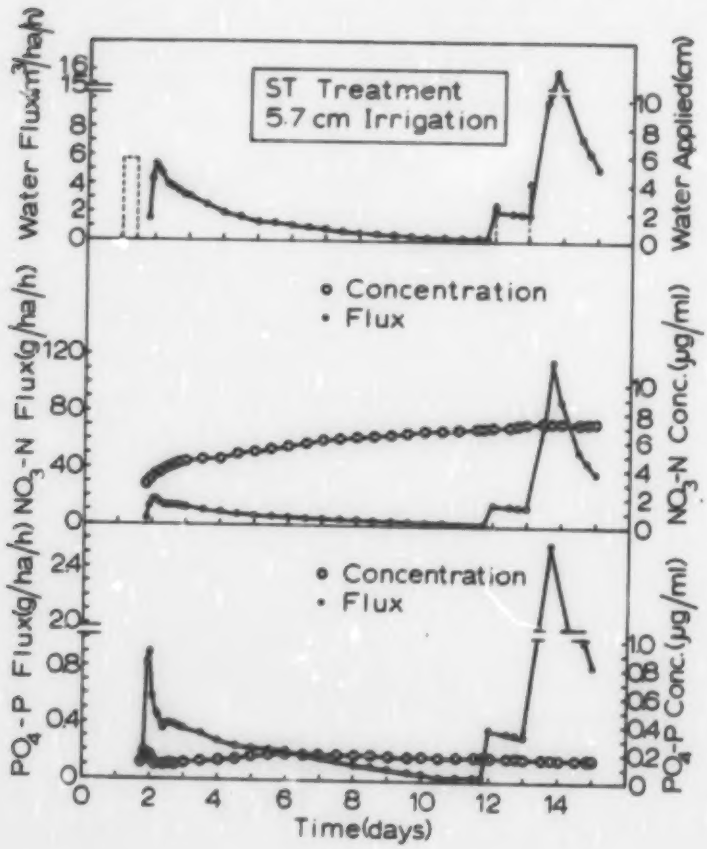


FIGURE 24. Fluxes of drainage water, NO_3-N and PO_4-P and concentrations of NO_3-N and PO_4-P in subsurface drainage from the ST soil management treatment during a 14-day period (February 11-24, 1975) following a 5.7-cm irrigation. Water was applied continuously over a 14-hour period which occurred three months after a quarterly application of 530 kg/ha of an 8-2-8 fertilizer. Rainfall occurred on days 11 and 13 for a total of 8.6 cm.

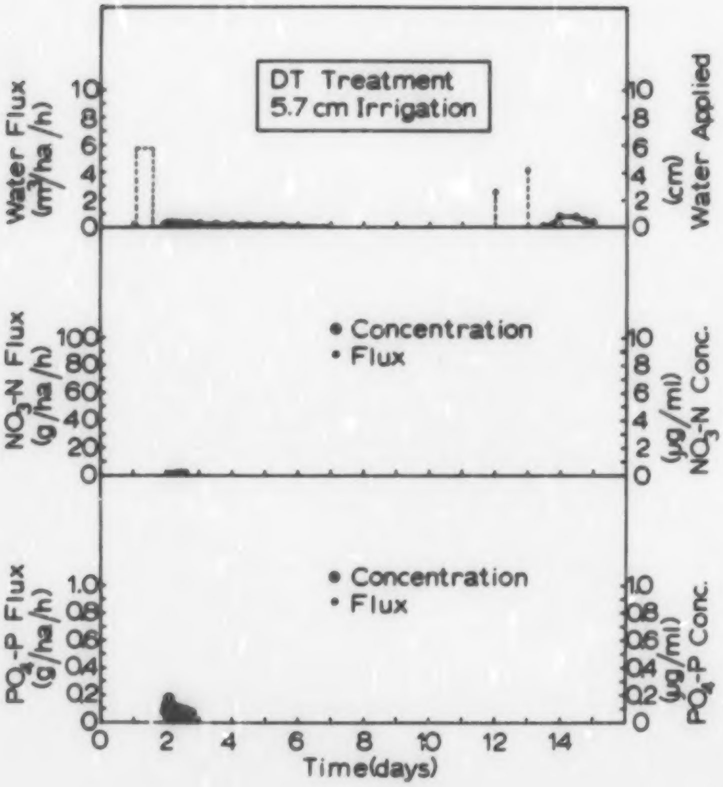


FIGURE 25. Fluxes of drainage water, NO_3-N and PO_4-P and concentrations of NO_3-N and PO_4-P in subsurface drainage from the DT soil management treatment during a 14-day period (February 11-24, 1975) following a 5.7-cm irrigation. Water was applied continuously over a 14-hour period which occurred three months after a quarterly application of 530 kg/ha of an 8-2-8 fertilizer. Rainfall occurred on days 11 and 13 for a total of 8.6 cm.

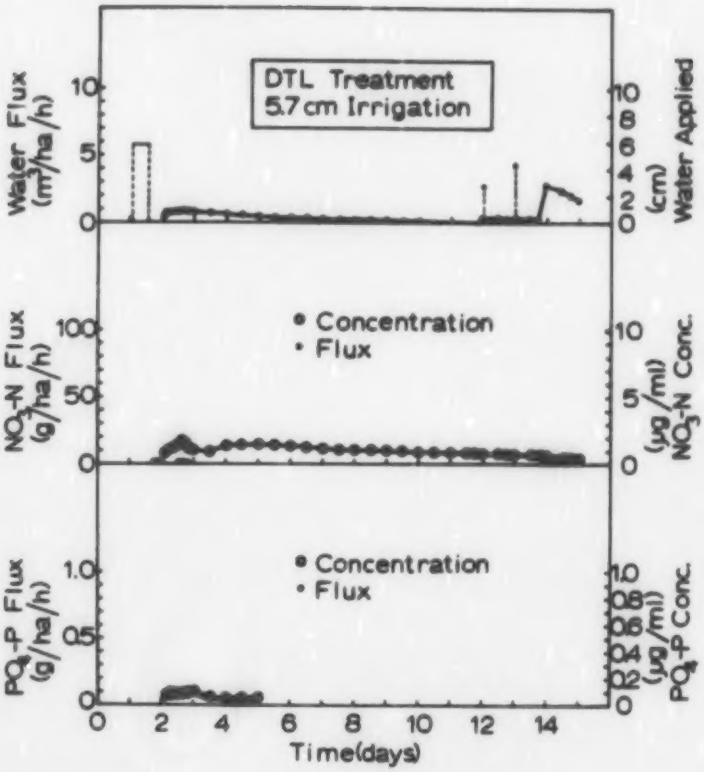


FIGURE 26. Fluxes of drainage water, NO_3-N and PO_4-P and concentrations of NO_3-N and PO_4-P in subsurface drainage from the DTL soil management treatment during a 14-day period (February 11-24, 1975) following a 5.7-cm irrigation. Water was applied continuously over a 14-hour period which occurred three months after a quarterly application of 530 kg/ha of an 8-2-8 fertilizer. Rainfall occurred on days 11 and 13 for a total of 8.6 cm.

Table 18. Concentration and flux of NO_3-N and PO_4-P in subsurface drainage water from ST, DT, and DTL treatments during a 14-day period (March 6-19, 1974) following a 16-cm irrigation. The plots were irrigated continuously over a 39-hour period immediately after a quarterly application of 530 kg/ha of an 8-2-8 fertilizer. Rainfall also occurred on days 9 and 10. Water table height (W.T. ht.) are presented.

			Surface Tilled						Deep Tilled						Deep Tilled Limed					
Day	Time	Rain fall	Flow Rate	W.T. Ht.	NO_3-N Conc.	PO_4-P Conc.	NO_3-N Flux	PO_4-P Flux	Flow Rate	W.T. Ht.	NO_3-N Conc.	PO_4-P Conc.	NO_3-N Flux	PO_4-P Flux	Flow Rate	W.T. Ht.	NO_3-N Conc.	PO_4-P Conc.	NO_3-N Flux	PO_4-P Flux
		cm	α[b]	m	ppm		g/ha/hr		α	m	ppm		g/ha/hr		α	m	ppm		g/ha/hr	
0[a]			0.00	5.09	1.78	bmdl[c]	bmdl	bmdl	0.00	5.19	bmdl	bmdl	bmdl	bmdl	0.00	5.31	1.35	bmdl	bmdl	bmdl
1	0500	0.00	1.15	5.98	2.10	0.08	2.42	0.09	0.17	6.12	0.12	0.06	0.02	0.01	0.08	6.26	1.87	0.16	0.15	0.01
	0800		3.77		3.50	0.13	13.20	0.49	0.48		0.13	0.07	0.06	0.03	0.78		2.50	0.16	1.95	0.12
	1000		6.59		8.40	0.15	55.35	0.99	0.87		0.15	0.08	0.13	0.07	0.85		5.00	0.43	4.25	0.36
	1200		7.00		10.00	0.20	70.00	1.40	1.26		0.17	0.09	0.21	0.11	0.92		7.60	0.36	6.99	0.39
	1400		8.00		11.40	0.22	91.20	1.76	1.65		0.20	0.10	0.33	0.17	1.51		10.80	0.28	16.31	0.42
	1600		8.76		12.80	0.23	112.13	2.01	2.05		0.25	0.12	0.51	0.25	2.10		13.70	0.24	28.77	0.63
	1800		9.71		13.60	0.28	132.06	2.72	2.46		0.30	0.18	0.74	0.44	3.96		12.60	0.20	49.89	0.79
	2000		10.66		14.00	0.31	149.24	3.30	2.90		0.35	0.22	1.02	0.64	4.99		12.40	0.19	61.87	0.85
	2200		11.73		14.40	0.33	168.91	3.87	3.30		0.38	0.26	1.25	0.86	5.86		12.00	0.18	70.08	0.93
	2400		12.81		14.80	0.35	189.59	4.48	3.86		0.41	0.30	1.57	1.15	6.69		11.30	0.18	75.60	1.20
2	0400	0.00	15.78	6.37	15.75	0.35	251.00	5.50	4.69	6.12	0.60	0.33	2.69	1.48	7.52	6.60	11.10	0.18	83.47	1.60
	0600		16.89		16.20	0.36	273.62	6.08	4.86		0.88	0.29	4.26	1.41	7.95		11.00	0.19	87.45	1.51
	1000		20.32		13.00	0.36	264.16	7.32	5.16		1.31	0.23	6.82	1.18	8.78		10.80	0.20	94.82	1.75
	1200		19.75		12.00	0.36	237.00	7.11	5.21		1.50	0.20	7.81	1.04	7.07		10.40	0.22	73.53	1.55
	1600		14.58		11.80	0.37	172.04	5.39	4.63		2.06	0.15	9.54	0.70	5.82		10.20	0.22	59.36	1.31
	1800		11.70		11.70	0.37	136.89	4.40	4.36		2.30	0.14	10.03	0.61	5.20		10.10	0.23	52.52	1.20
	2000		10.51		11.60	0.37	121.92	3.89	3.92		2.13	0.13	8.35	0.53	4.85		10.00	0.23	48.50	1.14
	2400		8.23		11.40	0.37	93.82	3.05	3.31		1.90	0.13	6.29	0.43	3.75		9.80	0.24	36.75	0.90
3	1200	0.00	6.51	5.78	11.50	0.38	74.87	2.47	2.91	5.89	1.60	0.14	4.66	0.40	3.07	6.13	9.40	0.28	28.86	0.86
	1800		5.76		11.40	0.38	65.66	2.19	2.57		1.54	0.14	3.96	0.38	2.60		9.26	0.28	24.08	0.73
	2400		5.01		11.40	0.39	57.11	1.95	2.29		1.50	0.15	3.44	0.36	2.38		9.00	0.28	21.42	0.66
4	1200	0.00	4.41	5.65	11.40	0.39	50.27	1.72	2.02	5.74	1.40	0.15	2.83	0.30	2.11	5.99	8.80	0.28	18.52	0.59
	2400		3.81		11.80	0.41	44.96	1.56	1.76		1.40	0.15	2.46	0.26	1.83		8.60	0.28	15.74	0.51
5	1200	0.00	3.32	5.58	12.20	0.43	40.50	1.43	1.52	5.68	1.40	0.15	2.13	0.23	1.59	5.92	8.40	0.28	13.31	0.44
	2400		2.83		12.60	0.40	35.66	1.13	1.28		1.40	0.14	1.79	0.18	1.34		8.80	0.27	11.79	0.36
6	1200	0.00	2.53	5.53	13.00	0.38	32.89	0.96	1.15	5.63	1.50	0.14	1.72	0.16	1.18	5.87	9.40	0.26	11.09	0.31
	2400		2.23		13.40	0.34	29.88	0.76	1.02		1.60	0.10	1.63	0.10	1.02		9.80	0.25	9.99	0.25
7	1200	0.00	1.96	5.47	13.80	0.32	27.05	0.63	0.95	5.60	1.80	0.11	1.71	0.10	0.93	5.83	10.40	0.24	9.67	0.22
	2400		1.70		14.20	0.32	24.14	0.51	0.88		1.60	0.13	1.41	0.11	0.84		11.00	0.23	9.24	0.19
8	1200	0.00	1.50	5.42	14.40	0.27	21.60	0.41	0.85	5.57	1.40	0.14	1.18	0.11	0.75	5.80	11.20	0.22	8.40	0.16
	2400		1.30		14.80	0.25	19.24	0.33	0.81		1.30	0.15	1.05	0.12	0.66		11.40	0.22	7.52	0.14
9	1200	0.38	1.15	5.38	15.00	0.22	17.25	0.25	0.77	5.53	1.20	0.16	0.92	0.12	0.57	5.77	11.60	0.22	6.73	0.12
	2400		1.00		15.40	0.23	15.40	0.23	0.73		1.10	0.16	0.80	0.11	0.48		12.20	0.20	5.85	0.09
10	1200	2.03	1.28	5.34	15.70	0.23	20.09	0.29	0.69	5.69	1.00	0.16	0.69	0.11	0.44	5.72	13.00	0.18	5.65	0.08
	2400		1.56		16.20	0.22	25.27	0.34	0.66		0.90	0.14	0.59	0.09	0.39		13.60	0.16	5.30	0.05
11	1200	0.00	1.34	5.40	16.60	0.20	22.24	0.27	0.71	5.77	0.80	0.13	0.57	0.09	0.37	5.90	14.00	0.14	5.11	0.05
	2400		1.13		17.00	0.18	19.21	0.20	0.77		0.75	0.12	0.57	0.08	0.34		14.80	0.13	5.03	0.04
12	1200	0.00	1.11	5.37	17.50	0.16	19.42	0.18	0.79	5.60	0.70	0.11	0.55	0.08	0.33	5.83	15.60	0.12	5.07	0.04
	2400		1.10		18.00	0.14	19.80	0.15	0.82		0.65	0.10	0.53	0.08	0.31		16.00	0.11	4.96	0.03
13	1200	0.00	0.92	5.35	18.40	0.12	16.93	0.11	0.79	5.53	0.60	0.10	0.47	0.07	0.30	5.76	16.80	0.10	4.96	0.03
	2400		0.74		17.40	0.08	12.87	0.06	0.77		0.55	0.08	0.42	0.06	0.28		13.60	0.10	3.81	0.02
14	1200	0.00	0.63	5.34	16.20	0.06	10.13	0.04	0.70	5.48	0.50	0.07	0.35	0.05	0.27	5.70	10.60	0.10	2.86	0.02
	2400		0.51		15.00	bmdl	7.65	bmdl	0.64		0.40	0.06	0.25	0.04	0.26		8.00	0.10	2.08	0.02

[a] baseline readings were taken before study on 3/5/74

[b] m^3/ha/hr

[c] bmdl, concentration was below the minimum detection level. Minimum detection levels for NO_3-N and PO_4-P are 0.04 ppm and 0.06 ppm, respectively. Discharge values for concentration lower than these levels were not calculated.

Table 19. Concentrations and fluxes of NO_3-N and PO_4-P in subsurface drainage water from ST, DT and DTL treatments during a 14-day period (May 21, 1974 through June 3, 1974) following an 8.2 cm irrigation. The plots were irrigated continuously over a 20-hour period immediately after a quarterly application of 530 kg/ha of an 8-2-8 fertilizer. Rainfall occurred on days 13 and 14. Water table heights (W.T. ht.) are presented.

			Surface Tilled						Deep Tilled						Deep Tilled Limed					
Day	Time	Rain fall	Flow Rate	W.T. ht.	NO_3-N Conc.	PO_4-P Conc.	NO_3-N Flux	PO_4-P Flux	Flow Rate	W.T. ht.	NO_3-N Conc.	PO_4-P Conc.	NO_3-N Flux	PO_4-P Flux	Flow Rate	W.T. ht.	NO_3-N Conc.	PO_4-P Conc.	NO_3-N Flux	PO_4-P Flux
		cm	b	m	ppm		g/ha/hr		b	m	ppm		g/ha/hr		b	m	ppm		g/ha/hr	
0[a]			0.06	5.43	3.42	0.11	0.21	0.01	0.27	5.49	0.40	bmdl[c]	0.11	bmdl	0.01	5.66	0.00	bmdl	0.01	bmdl
1	0400	0.00	0.85	5.36	4.00	0.11	3.42	0.09	0.79	5.48	0.40	bmdl	0.31	bmdl	0.18	5.58	1.40	bmdl	0.25	bmdl
	0800		0.89		4.00	0.12	3.42	0.10	0.78		0.40	bmdl	0.31	bmdl	0.16		1.40	bmdl	0.22	bmdl
	1200		0.85		4.00	0.13	3.42	0.11	0.77		0.40	bmdl	0.31	bmdl	0.15		1.40	bmdl	0.21	bmdl
	1600		0.79		4.00	0.15	3.00	0.13	0.76		0.40	bmdl	0.30	bmdl	0.12		1.39	bmdl	0.17	bmdl
	2000		0.69		4.00	0.19	2.90	0.13	0.75		0.40	bmdl	0.30	bmdl	0.10		1.30	0.07	0.13	0.01
	2200		0.63		4.00	0.21	2.60	0.13	0.76		0.40	bmdl	0.30	bmdl	0.11		1.20	0.09	0.13	0.01
	2400		0.63		4.00	0.22	2.31	0.14	0.86		0.40	0.06	0.34	0.05	0.11		1.20	0.11	0.13	0.01
2	0400	0.00	0.92	5.99	4.00	0.23	3.66	0.21	1.17	6.11	0.30	0.07	0.35	0.08	0.36	6.27	1.50	0.16	0.51	0.05
	0600		1.80		4.20	0.26	6.20	0.39	1.56		0.40	0.16	0.62	0.25	0.75		2.00	0.11	3.00	0.07
	0800		2.42		4.50	0.25	10.89	0.61	2.11		0.50	0.22	1.06	0.46	1.32		4.00	0.07	9.20	0.09
	1000		5.10		5.50	0.26	28.05	1.65	2.60		0.60	0.16	1.70	0.40	2.67		5.00	0.07	13.35	0.10
	1200		7.45		7.00	0.26	52.15	1.96	3.02		0.70	0.13	2.11	0.38	3.57		6.00	0.07	21.42	0.25
	1400		9.08		7.50	0.27	68.10	2.50	3.50		1.35	0.09	5.00	0.30	4.25		6.00	0.07	27.50	0.30
	1600		10.00		8.00	0.27	73.00	2.80	3.31		2.00	0.07	6.62	0.22	4.60		7.00	0.07	32.20	0.32
	2000		11.62		9.00	0.30	106.58	3.49	2.72		2.00	0.06	5.44	0.16	3.80		9.00	0.07	34.76	0.27
	2400		9.80		10.00	0.30	98.00	2.99	2.33		2.00	0.06	4.66	0.14	2.90		11.76	0.06	35.00	0.18
3	0400	0.00	7.18	5.82	11.50	0.31	82.57	2.22	2.06	5.91	2.00	0.06	4.00	0.12	2.49	6.05	13.65	0.06	36.00	0.16
	0800		5.41		12.50	0.31	67.62	1.68	1.81		2.00	bmdl	3.62	bmdl	2.16		15.00	bmdl	33.50	bmdl
	1200		4.41		13.00	0.30	57.30	1.36	1.66		2.00	bmdl	3.32	bmdl	1.86		17.76	bmdl	33.00	bmdl
	1600		3.71		12.60	0.29	49.00	1.20	1.52		2.00	bmdl	3.04	bmdl	1.66		19.00	bmdl	32.50	bmdl
	2000		3.33		11.70	0.28	41.50	1.05	1.39		2.00	bmdl	2.70	bmdl	1.56		19.40	bmdl	32.10	bmdl
	2400		3.09		11.00	0.28	33.99	0.87	1.27		2.00	bmdl	2.54	bmdl	1.48		19.20	bmdl	32.00	bmdl
4	0400	0.00	2.80	5.62	11.70	0.27	33.60	0.77	1.20	5.73	2.00	bmdl	2.40	bmdl	1.41	5.90	21.10	bmdl	31.90	bmdl
	0800		2.70		12.00	0.26	33.60	0.76	1.17		2.00	bmdl	2.34	bmdl	1.38		22.00	bmdl	31.60	bmdl
	1200		2.58		13.00	0.25	33.56	0.65	1.09		2.10	bmdl	2.29	bmdl	1.26		25.00	bmdl	31.00	bmdl
	1600		2.35		13.40	0.22	31.98	0.55	0.99		2.25	bmdl	2.21	bmdl	1.19		27.50	bmdl	31.20	bmdl
	2000		2.31		13.80	0.21	31.98	0.52	0.96		2.30	bmdl	2.20	bmdl	1.11		28.30	bmdl	31.10	bmdl
	2400		2.10		14.50	0.20	31.61	0.44	0.93		2.36	bmdl	2.20	bmdl	1.06		30.00	bmdl	31.20	bmdl
5	0800	0.00	2.07	5.56	10.30	0.18	21.13	0.39	0.87	5.66	2.48	bmdl	2.12	bmdl	0.99	5.86	27.50	bmdl	27.00	bmdl
	1200		1.97		10.60	0.18	20.80	0.36	0.86		2.50	bmdl	2.12	bmdl	0.95		26.31	bmdl	25.00	bmdl
	1800		1.81		10.00	0.18	17.40	0.36	0.80		2.61	bmdl	2.09	bmdl	0.91		22.00	bmdl	20.00	bmdl
	2400		1.67		10.50	0.20	17.50	0.32	0.75		2.66	bmdl	2.00	bmdl	0.86		17.50	bmdl	16.70	bmdl
6	0800	0.00	1.58	5.48	10.60	0.21	16.00	0.31	0.72	5.61	2.50	bmdl	1.85	bmdl	0.76	5.78	17.50	bmdl	13.00	bmdl
	1200		1.50		10.60	0.22	15.90	0.36	0.71		2.46	bmdl	1.75	bmdl	0.70		17.50	bmdl	12.25	bmdl
	1800		1.40		10.51	0.23	15.00	0.31	0.70		2.61	bmdl	1.68	bmdl	0.65		17.50	bmdl	11.50	bmdl
	2400		1.26		10.40	0.26	13.10	0.29	0.67		2.26	bmdl	1.50	bmdl	0.62		17.90	bmdl	10.85	bmdl
7	0800	0.00	1.20	5.42	10.67	0.25	12.40	0.26	0.66	5.57	2.05	bmdl	1.38	bmdl	0.58	5.75	17.20	bmdl	9.90	bmdl
	1200		1.12		10.80	0.25	12.09	0.28	0.63		2.00	bmdl	1.25	bmdl	0.55		17.00	bmdl	9.35	bmdl
	1800		1.10		10.80	0.25	11.20	0.23	0.61		1.86	bmdl	1.10	bmdl	0.53		16.20	bmdl	8.30	bmdl
	2400		0.98		10.80	0.22	10.58	0.21	0.57		1.75	bmdl	1.00	bmdl	0.49		15.50	bmdl	7.60	bmdl
8	0800	0.00	0.92	5.39	10.72	0.20	9.70	0.19	0.56	5.53	1.68	bmdl	0.92	bmdl	0.47	5.69	16.35	bmdl	6.80	bmdl
	1200		0.90		10.70	0.20	9.63	0.18	0.53		1.61	bmdl	0.89	bmdl	0.45		16.00	bmdl	6.30	bmdl
	1800		0.86		10.70	0.18	9.10	0.17	0.51		1.58	bmdl	0.82	bmdl	0.43		13.00	bmdl	5.80	bmdl
	2400		0.84		10.70	0.18	8.98	0.15	0.49		1.53	bmdl	0.75	bmdl	0.39		12.00	bmdl	4.68	bmdl
9	0800	0.00	0.79	5.35	10.15	0.18	7.80	0.15	0.49	5.50	1.32	bmdl	0.69	bmdl	0.36	5.66	10.70	bmdl	6.00	bmdl
	1200		0.77		9.90	0.18	7.62	0.14	0.49		1.23	bmdl	0.62	bmdl	0.35		10.00	bmdl	3.50	bmdl
	1800		0.74		9.97	0.18	7.38	0.13	0.49		1.12	bmdl	0.57	bmdl	0.32		10.00	bmdl	3.10	bmdl
	2400		0.71		10.27	0.18	7.29	0.12	0.49		1.00	bmdl	0.49	bmdl	0.31		10.00	bmdl	3.10	bmdl
10	1200	0.00	0.63	5.36	10.50	0.17	6.60	0.11	0.46	5.47	1.47	bmdl	0.67	bmdl	0.28	5.63	9.50	bmdl	2.60	bmdl
	2400		0.57		10.50	0.17	5.98	0.10	0.39		1.63	bmdl	0.66	bmdl	0.26		8.00	bmdl	1.90	bmdl
11	1200	0.00	0.50	5.32	10.05	0.16	5.00	0.08	0.35	5.65	1.80	bmdl	0.63	bmdl	0.22	5.61	7.80	bmdl	1.70	bmdl
	2400		0.43		9.60	0.15	4.13	0.06	0.36		1.76	bmdl	0.62	bmdl	0.20		7.50	bmdl	1.50	bmdl
12	1200	0.00	0.43	5.31	9.49	0.16	4.10	0.06	0.33	5.66	1.62	bmdl	0.53	bmdl	0.19	5.59	7.25	bmdl	1.30	bmdl
	2400		0.47		9.36	0.16	4.00	0.06	0.32		1.50	bmdl	0.48	bmdl	0.17		7.00	bmdl	1.10	bmdl
13	1200	0.64	0.40	5.29	9.20	0.13	3.60	0.05	0.29	5.63	1.66	bmdl	0.42	bmdl	0.15	5.58	7.00	bmdl	1.00	bmdl
	2400		0.38		9.00	0.13	3.40	0.05	0.67		1.40	bmdl	0.94	bmdl	0.13		7.00	bmdl	0.90	bmdl
14	1200	2.03	0.34	5.30	9.00	0.12	2.50	0.05	0.66	5.56	1.38	bmdl	0.88	bmdl	0.11	5.60	7.00	bmdl	0.90	bmdl
	2400		0.30		9.00	0.11	2.50	0.04	0.62		1.32	bmdl	0.82	bmdl	0.10		7.00	bmdl	0.70	bmdl

a baseline readings were taken before study on 5/19/74

b m^3/ha/hr

c bmdl, concentration was below the minimum detection level. Minimum detection levels for NO_3-N and PO_4-P are 0.06 ppm and 0.06 ppm, respectively. Discharge values for concentrations lower than these levels were not calculated.

Table 20. Concentrations and fluxes of NO_3-N and PO_4-P in subsurface drainage water from ST, DT, and DTL treatments during a 14-day period (March 17-30, 1975) after a 2.4 cm irrigation. The plots were irrigated continuously over a 6-hours period immediately following a quarterly application of 530 kg/ha of an 8-2-8 fertilizer. Rainfall occurred on days 2 and 3. Water table height (W.T. ht.) are presented.

			Surface Tilled						Deep Tilled						Deep Tilled Limed					
Day	Time	Rain fall	Flow Rate	W.T. Ht.	NO_3-N Conc.	PO_4-P Conc.	NO_3-N Flux	PO_4-P Flux	Flow Rate	W.T. Ht.	NO_3-N Conc.	PO_4-P Conc.	NO_3-N Flux	PO_4-P Flux	Flow Rate	W.T. Ht.	NO_3-N Conc.	PO_4-P Conc.	NO_3-N Flux	PO_4-P Flux
		cm	α[b]	-m-	— ppm —		—g/ha/hr —		α	-m-	— ppm —		—g/ha/hr —		α	-m-	— ppm —		—g/ha/hr —	
0[a]		0.00	0.00	5.19	0.30	0.10	0.00	0.00	0.00	5.34	bmdl[c]	bmdl	0.00	bmdl	0.00	5.47	0.06	bmdl	0.00	bmdl
1	1400	0.00	0.00	5.20	0.47	0.12	0.00	0.00	0.00	5.47	0.04	bmdl	0.00	bmdl	0.02	5.48	0.09	bmdl	0.00	bmdl
	1800		0.11		0.55	0.14	0.06	0.02	0.13		0.06	bmdl	0.01	bmdl	0.02		0.09	bmdl	0.00	bmdl
	2000		0.31		0.70	0.16	0.22	0.05	0.16		0.08	bmdl	0.01	bmdl	0.02		0.09	bmdl	0.00	bmdl
	2200		0.47		0.90	0.18	0.42	0.08	0.19		0.07	bmdl	0.01	bmdl	0.02		0.09	bmdl	0.00	bmdl
	2400		0.57		1.20	0.20	0.68	0.11	0.22		0.07	bmdl	0.02	bmdl	0.03		0.09	bmdl	0.00	bmdl
2	0300	0.64	0.59	5.24	1.45	0.17	0.86	0.10	0.27	5.56	0.05	bmdl	0.01	bmdl	0.03	5.59	0.09	bmdl	0.00	bmdl
	0600		0.60		1.65	0.15	0.99	0.09	0.33		0.05	bmdl	0.02	bmdl	0.03		0.09	bmdl	0.00	bmdl
	1200		0.65		2.00	0.10	1.40	0.07	0.41		0.07	bmdl	0.03	bmdl	0.06		0.09	bmdl	0.00	bmdl
	1600		0.72		2.15	0.09	1.55	0.06	0.45		0.05	bmdl	0.02	bmdl	0.06		0.08	bmdl	0.00	bmdl
	1800		0.75		2.30	0.09	1.75	0.07	0.45		0.05	bmdl	0.02	bmdl	0.05		0.07	bmdl	0.00	bmdl
	2000		0.77		2.40	0.09	1.85	0.07	0.45		0.05	bmdl	0.02	bmdl	0.05		0.06	bmdl	0.00	bmdl
	2400		0.82		2.50	0.09	2.05	0.07	0.45		0.05	bmdl	0.02	bmdl	0.05		0.05	bmdl	0.00	bmdl
3	0400	2.29	1.20	5.46	2.59	0.09	3.10	0.10	0.45	5.77	0.05	bmdl	0.02	bmdl	0.07	5.75	0.05	bmdl	0.00	bmdl
	0800		1.55		2.68	0.09	4.15	0.14	0.44		0.05	bmdl	0.02	bmdl	0.08		0.06	bmdl	0.00	bmdl
	1200		1.92		2.80	0.09	5.38	0.17	0.75		0.05	bmdl	0.04	bmdl	0.33		0.10	bmdl	0.03	bmdl
	1600		2.29		2.90	0.10	6.64	0.23	0.93		0.15	bmdl	0.14	bmdl	0.57		0.18	bmdl	0.10	bmdl
	2000		2.30		3.05	0.10	7.02	0.23	0.92		0.22	bmdl	0.20	bmdl	0.58		0.22	bmdl	0.13	bmdl
	2400		2.31		3.15	0.12	7.28	0.28	0.91		0.20	bmdl	0.18	bmdl	0.58		0.35	bmdl	0.20	bmdl
4	1200	0.00	2.06	5.51	3.50	0.14	7.21	0.29	0.88	5.69	0.08	bmdl	0.07	bmdl	0.56	5.76	0.70	bmdl	0.39	bmdl
	2400		1.81		3.90	0.24	7.06	0.43	0.84		0.16	bmdl	0.13	bmdl	0.54		1.08	bmdl	0.58	bmdl
5	1200	0.00	1.55	5.49	4.80	0.24	7.44	0.37	0.79	5.64	0.04	bmdl	0.03	bmdl	0.49	5.75	2.00	bmdl	0.98	bmdl
	2400		1.28		5.30	0.24	6.78	0.31	0.74		0.04	bmdl	0.03	bmdl	0.43		2.40	bmdl	1.03	bmdl
6	1200	0.00	1.12	5.42	5.10	0.24	5.71	0.27	0.69	5.56	0.05	bmdl	0.03	bmdl	0.39	5.70	2.20	bmdl	0.86	bmdl
	2400		0.95		4.95	0.24	4.70	0.23	0.64		0.05	bmdl	0.03	bmdl	0.34		2.25	bmdl	0.77	bmdl
7	1200	0.00	0.83	5.37	4.80	0.24	3.98	0.20	0.60	5.53	0.05	bmdl	0.03	bmdl	0.30	5.66	2.55	bmdl	0.77	bmdl
	2400		0.71		4.70	0.22	3.34	0.16	0.56		0.20	bmdl	0.11	bmdl	0.26		2.65	bmdl	0.69	bmdl
8	1200	0.00	0.62	5.34	4.80	0.22	2.98	0.14	0.52	5.49	0.04	bmdl	0.02	bmdl	0.22	5.62	2.40	bmdl	0.53	bmdl
	2400		0.52		4.90	0.21	2.55	0.11	0.48		bmdl	bmdl	bmdl	bmdl	0.18		2.15	bmdl	0.39	bmdl
9	1200	0.00	0.46	5.32	5.05	0.20	2.32	0.09	0.44	5.46	0.05	bmdl	0.02	bmdl	0.15	5.59	1.90	bmdl	0.29	bmdl
	2400		0.40		5.15	0.18	2.06	0.07	0.40		0.05	bmdl	0.02	bmdl	0.12		1.67	bmdl	0.20	bmdl
10	1200	0.00	0.35	5.31	5.30	0.16	1.86	0.06	0.38	5.44	0.05	bmdl	0.02	bmdl	0.10	5.56	1.30	bmdl	0.13	bmdl
	2400		0.29		4.90	0.14	1.42	0.04	0.35		0.04	bmdl	0.01	bmdl	0.08		1.10	bmdl	0.09	bmdl
11	1200	0.00	0.25	5.31	4.50	0.13	1.13	0.03	0.33	5.41	0.04	bmdl	0.01	bmdl	0.06	5.53	0.95	bmdl	0.06	bmdl
	2400		0.20		4.10	0.11	0.82	0.02	0.30		0.04	bmdl	0.01	bmdl	0.05		0.80	bmdl	0.04	bmdl
12	1200	0.00	0.16	5.31	3.70	0.09	0.59	0.01	0.28	5.39	bmdl	bmdl	bmdl	bmdl	0.04	5.51	0.65	bmdl	0.03	bmdl
	2400		0.12		3.25	0.10	0.39	0.01	0.26		bmdl	bmdl	bmdl	bmdl	0.03		0.60	bmdl	0.02	bmdl
13	1200	0.00	0.09	5.30	2.85	0.10	0.26	0.01	0.25	5.38	bmdl	bmdl	bmdl	bmdl	0.03	5.49	0.55	bmdl	0.02	bmdl
	2400		0.06		2.45	0.11	0.15	0.01	0.24		bmdl	bmdl	bmdl	bmdl	0.02		0.50	bmdl	0.01	bmdl
14	1200	0.00	0.03	5.28	2.00	0.14	0.06	0.00	0.23	5.36	bmdl	bmdl	bmdl	bmdl	0.01	5.48	0.45	bmdl	0.00	bmdl
	2400		0.01		1.60	0.16	0.02	0.00	0.23		bmdl	bmdl	bmdl	bmdl	0.01		0.40	bmdl	0.00	bmdl

a baseline readings were taken before study on 3/15/75

b m^3/ha/hr

c bmdl, concentration was below the minimum detection level. Minimum detection levels for NO_3-N and PO_4-P are 0.04 ppm and 0.06 ppm, respectively. Discharge values for concentrations lower than these levels were not calculated.

Table 21. Concentrations and fluxes of NO_3-N and PO_4-P in subsurface drainage water from ST, DT, and DTL treatments during a 14-day period (February 11-24, 1975) following a 5.7 cm irrigation. Plots were irrigated continuously over a 14-hour period. Rainfall occurred on days 11 and 13. Water table height (W.T. ht.) are presented.

			Surface Tilled						Deep Tilled						Deep Tilled Limed					
Day	Time	Rain fall	Flow Rate	W.T. Ht.	NO_3-N Conc.	PO_4-P Conc.	NO_3-N Flux	PO_4-P Flux	Flow Rate	W.T. Ht.	NO_3-N Conc.	PO_4-P Conc.	NO_3-N Flux	PO_4-P Flux	Flow Rate	W.T. Ht.	NO_3-N Conc.	PO_4-P Conc.	NO_3-N Flux	PO_4-P Flux
		cm	[b]	m	ppm		g/ha/hr		[b]	m	ppm		g/ha/hr		[b]	m	ppm		g/ha/hr	
0[a]			0.00	5.19	0.8[illegible]	0.11	0.00	0.00	0.00	5.08	bmdl[c]	bmdl	0.00	0.00	0.00	5.30	0.07	bmdl	0.00	0.00
1	1000	0.00	0.00	5.64	2.60	0.12	0.00	0.00	0.00	5.47	bmdl	bmdl	0.00	0.00	0.00	5.58	0.12	bmdl	0.00	0.00
	2000		1.53		2.80	0.14	4.28	0.21	0.05		bmdl	bmdl	bmdl	bmdl	0.00		0.12	bmdl	0.00	0.00
	2200		4.31		3.10	0.19	13.36	0.82	0.18		bmdl	0.08	bmdl	0.01	0.00		0.12	bmdl	0.00	0.00
	2400		5.32		3.50	0.17	16.62	0.90	0.25		bmdl	0.10	bmdl	0.03	0.00		0.12	bmdl	0.00	0.00
2	0200	0.00	5.00	5.70	3.57	0.13	18.00	0.58	0.28	5.60	0.06	0.18	0.01	0.05	0.55	5.72	0.85	0.08	0.47	0.05
	0300		4.89		3.60	0.10	17.60	0.49	0.30		0.06	0.16	0.01	0.05	0.77		0.95	0.08	0.73	0.06
	0400		4.75		3.66	0.10	17.10	0.47	0.31		0.05	0.12	0.02	0.04	0.76		1.00	0.08	0.78	0.06
	0600		4.46		3.70	0.10	16.50	0.45	0.31		0.06	0.10	0.02	0.03	0.74		1.20	0.08	0.89	0.06
	0800		3.85		3.87	0.10	14.70	0.37	0.31		0.05	0.09	0.02	0.03	0.73		1.30	0.08	0.95	0.06
	1000		3.40		4.00	0.10	13.70	0.36	0.30		0.06	0.06	0.01	0.02	0.73		1.35	0.08	0.98	0.06
	1200		3.71		4.05	0.10	15.03	0.40	0.29		0.06	0.06	0.01	0.02	0.78		1.38	0.08	1.07	0.06
	1400		3.60		4.10	0.11	14.76	0.39	0.28		bmdl	0.07	bmdl	0.02	0.81		1.60	0.09	1.30	0.07
	1600		3.53		4.20	0.11	14.75	0.39	0.28		bmdl	0.07	bmdl	0.02	0.80		1.80	0.09	1.44	0.07
	1800		3.43		4.30	0.11	14.75	0.39	0.28		bmdl	0.06	bmdl	0.01	0.79		1.55	0.09	1.15	0.07
	2000		3.22		4.40	0.11	14.19	0.37	0.27		0.06	bmdl	0.01	bmdl	0.79		1.30	0.09	1.03	0.08
	2400		3.02		4.50	0.12	13.59	0.36	0.25		0.06	bmdl	0.02	bmdl	0.78		1.15	0.11	0.90	0.09
3	1200	0.00	2.51	5.65	4.60	0.13	11.55	0.33	0.22	5.59	bmdl	0.06	bmdl	0.01	0.70	5.72	1.00	0.08	0.70	0.05
	2400		1.97		4.70	0.14	9.26	0.28	0.18		bmdl	bmdl	bmdl	bmdl	0.62		1.40	0.08	0.87	0.06
4	1200	0.00	1.61	5.55	5.00	0.15	8.05	0.26	0.15	5.50	bmdl	bmdl	bmdl	bmdl	0.53	5.60	1.45	0.08	0.76	0.03
	2400		1.34		5.20	0.17	6.97	0.23	0.12		bmdl	bmdl	bmdl	bmdl	0.43		1.55	0.08	0.67	0.03
5	1200	0.00	1.22	5.47	5.40	0.18	6.59	0.22	0.10	5.53	bmdl	bmdl	bmdl	bmdl	0.37	5.63	1.45	bmdl	0.54	bmdl
	2400		1.11		5.60	0.19	6.22	0.21	0.07		bmdl	bmdl	bmdl	bmdl	0.31		1.40	bmdl	0.43	bmdl
6	1200	0.00	0.97	5.41	5.80	0.19	5.63	0.18	0.06	5.48	bmdl	bmdl	bmdl	bmdl	0.27	5.59	1.30	bmdl	0.35	bmdl
	2400		0.84		6.00	0.18	5.06	0.16	0.04		bmdl	bmdl	bmdl	bmdl	0.24		1.20	bmdl	0.29	bmdl
7	1200	0.00	0.73	5.37	6.10	0.18	4.45	0.14	0.03	5.45	bmdl	bmdl	bmdl	bmdl	0.21	5.55	1.15	bmdl	0.24	bmdl
	2400		0.62		6.20	0.18	3.86	0.11	0.02		bmdl	bmdl	bmdl	bmdl	0.18		1.10	bmdl	0.20	bmdl
8	1200	0.00	0.53	5.35	6.30	0.18	3.36	0.10	0.01	5.41	bmdl	bmdl	bmdl	bmdl	0.16	5.53	1.06	bmdl	0.16	bmdl
	2400		0.44		6.40	0.17	2.82	0.08	0.01		bmdl	bmdl	bmdl	bmdl	0.13		1.03	bmdl	0.13	bmdl
9	1200	0.00	0.36	5.36	6.50	0.17	2.36	0.06	0.00	5.38	bmdl	bmdl	bmdl	bmdl	0.11	5.50	1.00	bmdl	0.11	bmdl
	2400		0.29		6.60	0.17	1.91	0.05	0.00		bmdl	bmdl	bmdl	bmdl	0.09		0.96	bmdl	0.09	bmdl
10	1200	0.00	0.26	5.33	6.70	0.17	1.66	0.04	0.00	5.35	bmdl	bmdl	bmdl	bmdl	0.08	5.48	0.93	bmdl	0.07	bmdl
	2400		0.20		6.80	0.17	1.36	0.03	0.00		bmdl	bmdl	bmdl	bmdl	0.07		0.90	bmdl	0.06	bmdl
11	1200	2.79	0.19	5.37	6.85	0.17	1.30	0.03	0.00	5.36	bmdl	bmdl	bmdl	bmdl	0.06	5.49	0.87	bmdl	0.05	bmdl
	1800		0.18		6.90	0.17	1.24	0.03	0.00		bmdl	bmdl	bmdl	bmdl	0.05		0.85	bmdl	0.04	bmdl
	2400		2.16		6.95	0.17	15.01	0.37	0.13		bmdl	bmdl	bmdl	bmdl	0.37		0.84	bmdl	0.31	bmdl
12	1200	0.00	2.01	5.34	7.00	0.17	14.07	0.34	0.15	5.38	bmdl	bmdl	bmdl	bmdl	0.37	5.61	0.81	bmdl	0.29	bmdl
	1800		1.96		7.10	0.17	13.92	0.33	0.16		bmdl	bmdl	bmdl	bmdl	0.36		0.79	bmdl	0.28	bmdl
	2400		1.90		7.20	0.17	13.68	0.32	0.17		bmdl	bmdl	bmdl	bmdl	0.36		0.78	bmdl	0.28	bmdl
13	1200	4.30	9.93	5.09	7.23	0.16	71.79	1.59	0.20	5.90	bmdl	bmdl	bmdl	bmdl	0.33	5.81	0.76	bmdl	0.26	bmdl
	1800		15.98		7.25	0.16	115.86	2.57	0.23		bmdl	bmdl	bmdl	bmdl	0.30		0.72	bmdl	0.22	bmdl
	2400		12.17		7.26	0.16	88.35	1.95	0.80		bmdl	bmdl	bmdl	bmdl	2.85		0.70	bmdl	2.00	bmdl
14	1200	0.00	7.28	5.08	7.27	0.16	53.00	1.16	0.60	5.89	bmdl	bmdl	bmdl	bmdl	2.41	5.88	0.62	bmdl	1.49	bmdl
	1800		6.21		7.28	0.16	45.21	0.99	0.58		bmdl	bmdl	bmdl	bmdl	2.08		0.57	bmdl	1.18	bmdl
	2400		5.13		7.30	0.16	37.45	0.82	0.48		bmdl	bmdl	bmdl	bmdl	1.75		0.53	bmdl	0.93	bmdl

[a] baseline readings were taken before study on 2/9/75

[b] m^3/ha/hr

[c] bmdl, concentration was below the minimum detection level. Minimum detection levels for NO_3-N and PO_4-P are 0.06 ppm and 0.06 ppm, respectively. Discharge values for concentrations lower than these levels were not calculated.

Table 22. Concentrations, total discharges, and estimated percentage losses of NO_3-N and PO_4-P in surface runoff water and subsurface drainage for 14-day periods following irrigation amounts of 16.0, 8.2, 5.7 and 2.4 cm.

Irr. Applied	Soil Treat.	NO_3-N Conc Mean	NO_3-N Conc Range	PO_4-P Conc Mean	PO_4-P Conc Range	Total Flow	NO_3-N Disc.	PO_4-P Disc.	NO_3-N % Loss	PO_4-P % Loss
— cm —		ppm		ppm		m^3/ha	kg	g		
16.0	ST	12.00	1.78-18.40	0.30	bmdl-0.43	1127.74	14.40	387.84	33.98	8.39
	DT	1.14	bmdl[a]-2.30	0.15	bmdl-0.33	938.06	0.57	72.00	1.34	1.56
	DTL	9.83	1.35-16.80	0.22	bmdl-0.28	485.16	5.13	106.80	12.10	2.31
	STRO	0.00		0.00		0.00	0.00	0.00	0.00	0.00
	DTRO	4.64		0.59		91.70	0.43	54.10	1.01	1.17
	DTLRO	4.28		0.51		148.70	0.64	75.84	1.51	1.64
8.2	ST	9.63	3.42-14.50	0.19	0.11-0.31	511.83	5.38	138.06	12.69	3.00
	DT	1.98	0.40- 2.66	bmdl	bmdl-0.22	268.39	0.45	6.71	1.06	0.14
	DTL	11.81	0.60-30.00	bmdl	bmdl-0.16	237.42	3.48	5.42	8.21	0.12
	STRO	0.00		0.00		0.00	0.00	0.00	0.00	0.00
	DTRO	3.72		0.74		11.00	0.04	8.14	0.09	0.18
	DTLRO	3.76		0.44		80.00	0.30	35.20	0.71	0.76
5.7	ST	5.73	0.82- 7.30	0.15	0.11-0.19	797.70	4.44	123.22	10.48	2.67
	DT	bmdl	bmdl- 0.06	0.06	bmdl-0.18	51.61	trace[b]	0.77	neg	0.02
	DTL	1.00	0.07- 1.80	bmdl	bmdl-0.11	157.42	0.14	3.74	0.33	0.08
	STRO	bmdl		bmdl		1.85[c]	0.00	0.00	0.00	0.00
	DTRO	bmdl		bmdl		28.91	0.00	0.00	0.00	0.00
	DTLRO	bmdl		bmdl		74.31	0.00	0.00	0.00	0.00
2.4	ST	3.68	0.30- 5.30	0.16	0.09-0.24	252.90	0.95	41.03	2.24	0.89
	DT	0.06	bmdl- 0.22	bmdl	bmdl-bmdl	154.84	0.01	trace	0.02	neg
	DTL	1.13	0.05- 2.65	bmdl	bmdl-bmdl	49.03	0.09	trace	0.21	neg
	STRO	0.42		0.78		0.07[c]	trace	0.05	neg[d]	neg
	DTRO	0.25		0.46		0.97	trace	0.45	neg	0.01
	DTLRO	0.25		0.35		1.66	trace	0.58	neg	0.01

[a] bmdl, concentration was below the minimum detection level. Minimum detection levels for NO_3-N and PO_4-P are 0.04 ppm and 0.06 ppm, respectively.

[b] trace, discharge values wereless than 0.01 kg for NO_3-N and 0.01 g for PO_4-P.

[c] Surface runoff for this period resulted from rainfall which occurred after irrigation.

[d] neg, loss was less than 0.01 percent.

Concentrations of NO_3-N in subsurface drainage following irrigation generally tended to increase with the quantity of water applied. For the 8.2 cm irrigation, maximum concentrations of NO_3-K were 14.50, 2.66, and 30 μg/ml for ST, DT, and DTL plots. For unknown reasons, the concentration of NO_3-N in drainage from DTL was especially large. For the 2.4 cm irrigation, maximum concentrations of NO_3-N were 5.37, 0.20, and 2.65 μg/ml for ST, DT, and DTL plots.

Especially noteworthy is the observation that drainage following the 5.7 cm irrigation which was applied 3 months after a quarterly fertilization initiated less discharge of nutrients from the soil profiles than when irrigation was applied within one or two days after application of fertilizer. For ST, DT, and DTL plots maximum concentrations of NO_3-N were 7.30, 0.06, and 1.55 μg/ml, respectively; whereas, maximum concentrations of PO_4-P were 0.19, 0.18, and 0.11 μg/ml, respectively. Thus the length of the time period between times of fertilization and a rainfall or irrigation event definitely is one of the factors resulting in enrichment of drainage water with nutrients.

Figures 24, 25, and 26 show the results of the 5.7 cm irrigation applied (beginning on February 11, 1975), 3 months after fertilization. The amount of irrigation was sufficient to give a flushing action in ST only for both NO_3-N and PO_4-P in that discharge peaks for both nutrients observed in ST drainage water were at approximately 1.5 days after the initiation of the irrigation. However, these peaks gradually subsided and the nutrient discharge curves returned to base level by the 11th day (February 21) following irrigation. On this data a rain occurred, followed by another on February 23, 1975, both of which totaled 7.17 cm. The additional rainfall initiated additional concentration and discharge peaks for both NO_3-N and PO_4-P in the ST plot, and a minor peak for NO_3-N in the DTL plot. The subsurface nutrient discharge peaks for the ST plot were very similar to those obtained following the 8.2 cm irrigation of May 21, 1974. However, the concentrations and nutrient discharges of the DT and DTL plots remained very low compared to that for ST. This phenomena could possibly be explained by less nitrification of NO_3-N in the deep-tilled plots.

Concentrations of PO_4-P in drainage tended to be relatively low compared to that for NO_3-N. For the ST plot, maximum concentrations of PO_4-P were 0.43, 0.31, and 0.24 μg/ml in subsurface drainage following irrigations of 16.0, 8.2, and 2.4 cm. For the DT plot, maximum concentrations of PO_4-P were 0.33, 0.22, and 0.06 μg/ml in subsurface drainage following irrigations of 16.0 8.2, and 2.4 cm. For the DTL plot, maximum concentrations of PO_4-P were 0.43, 0.16 and 0.06 μg/ml, respectively. For the ST plot these peak concentrations tended to occur several days earlier than those for DT or DTL plots.

The contribution of surface runoff water (Table 22) to the overall nutrient enrichment of the perimeter ditch water was low from the DT plots, less than 0.65 kg/ha NO_3-N for DTL (13% of the total loss) and less than 0.44 kg/ha for DT (77% of the total loss) after the 16.0 cm irrigation, and was zero for ST due to negligible water runoff from the ST area during all of the irrigation studies. During the 14-day period following the 8.2 cm irrigation (May 21 to June 3, 1974) the mean concentration of NO_3-N was 9.6, 2.0, and 11.8 μg/ml for the ST, DT and DTL plots, respectively, Discharges of NO_3-N were 5.4, 0.4, and 3.5 kg/ha, respectively.

Estimated percentage losses of NO_3-N in subsurface drainage were sizeable from the 16.0 and 8.2 cm irrigations (Table 22) for both ST and DTL treatments. During the 14-day periods, ST lost nitrogen equivalent to 34.0% and 12.7% of the nitrogen applied as fertilizer, respectively, while DT losses were equivalent to 1.34 and 1.06% and DTL losses were equivalent to 12.1 and 8.2%, respectively, for the 16.0 and 8.2 cm irrigations. Since ammonium and nitrate were the sources of N, only 45% of the applied N was originally in the nitrate state. Thus the losses with respect to percentages of applied NO_3-N were 68.0% and 25.2% for ST, and 25.8% and 16.6% for DTL following the 16.0 and 8.2 cm irrigations, respectively. Loss of PO_4-P from ST was 3.7 and 1.3% of applied phosphorus and 1.3 and 0.1% from DTL after the two irrigations, respectively. Losses of NO_3-N and PO_4-P generally were very small for the 5.7 and 2.4 cm irrigations.

Total drainage, NO_3-N discharge, and PO_4-P discharge during 14-day periods following the 16.0, 8.2, and 2.4 cm irrigations are presented in Fig. 27 as functions of the water input to the soil from rainfall plus irrigation. As shown previously in the report, drainage was always greatest from ST, least from DTL, and intermediate from DT. For all three soil management plots, drainage increased with total input of water from irrigation and rainfall. Discharge of NO_3-N and PO_4-P with subsurface drainage also tended to increase with total input of irrigation and rainfall. For any given amount of irrigation plus rainfall, considerably more N and P were discharged with drainage from ST than from either of the deep-tilled treatments. Although discharge of PO_4-P was similar in drainage from each of the deep-tilled plots, NO_3-N discharge from the DTL plot was greater than from DT for the 8.2 and 16.0 cm irrigations. For the 2.4 cm irrigation NO_3-N discharge was similar for DT and DTL. Since water flow was greater from DT than DTL plots, the greater discharge of NO_3-N from DTL following large irrigation events was associated with the larger NO_3-N concentrations observed in drainage from DTL than from DT. The larger NO_3-N concentrations could possibly be due to higher rates of nitrification for applied NH_4-N in the heavily limed DTL soil.

In Figs. 28, 29, and 30 water table depths at the midplane between parallel subsurface drains are plotted with time during 10-day periods following irrigations of 16.0, 8.2, and 5.7 cm for ST, DT, and DTL soil management plots.

Water table depths from the soil surface were generally deeper in the ST soil for a given rainfall event than in the DT and DTL soil profiles. Drainage in the DT and DTL soils was usually slower due to smaller values of hydraulic conductivity and clogging of soil adjacent to the drains. Higher water contents were thus commonly maintained in the surface DT and DTL soil due to slower drainage than the ST soil. Of the three irrigations, only the 16.0 cm irrigation resulted in midplane water tables rising to the soil surface. For the 16.0 cm irrigation the water table rise to the surface was slower for ST than DT and DTL, but the falling stage was obviously much faster for the ST plot. Water tables located at shallower depths in DT and DTL treatments suggest the occurrence of higher soil water contents

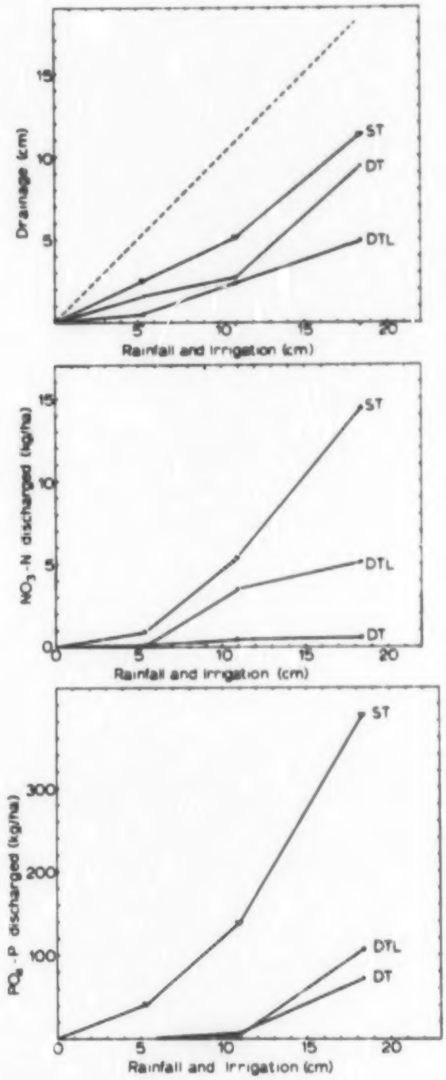


FIGURE 27. Total drainage, NO_3-N discharged, and PO_4-P discharged versus total rainfall and irrigation during three 14-day periods (16.0, 8.2, and 2.4 cm irrigations) for ST, DT and DTL soil management treatments.

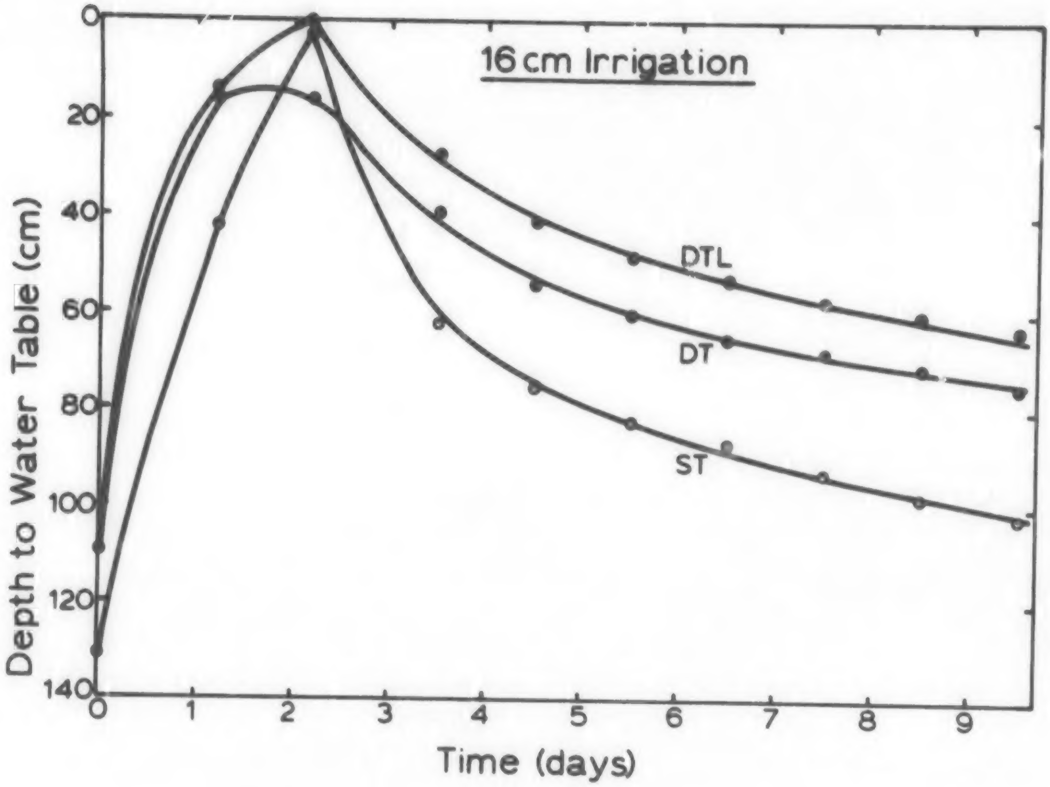


FIGURE 28. Time-dependence of water table depth measured at a point midway between two parallel drain tubes for a 16.0-cm irrigation (March 6-14, 1974) in ST, DT, and DTL plots. The water table depth is taken as a distance beneath a point of zero depth located midway between the elevations of the surface of the soil bed and the bottom of the water furrow. The elevations of the zero depth relative to mean sea level were 6.40 m for the ST and DTL plots and 6.28 m for the DT plot.

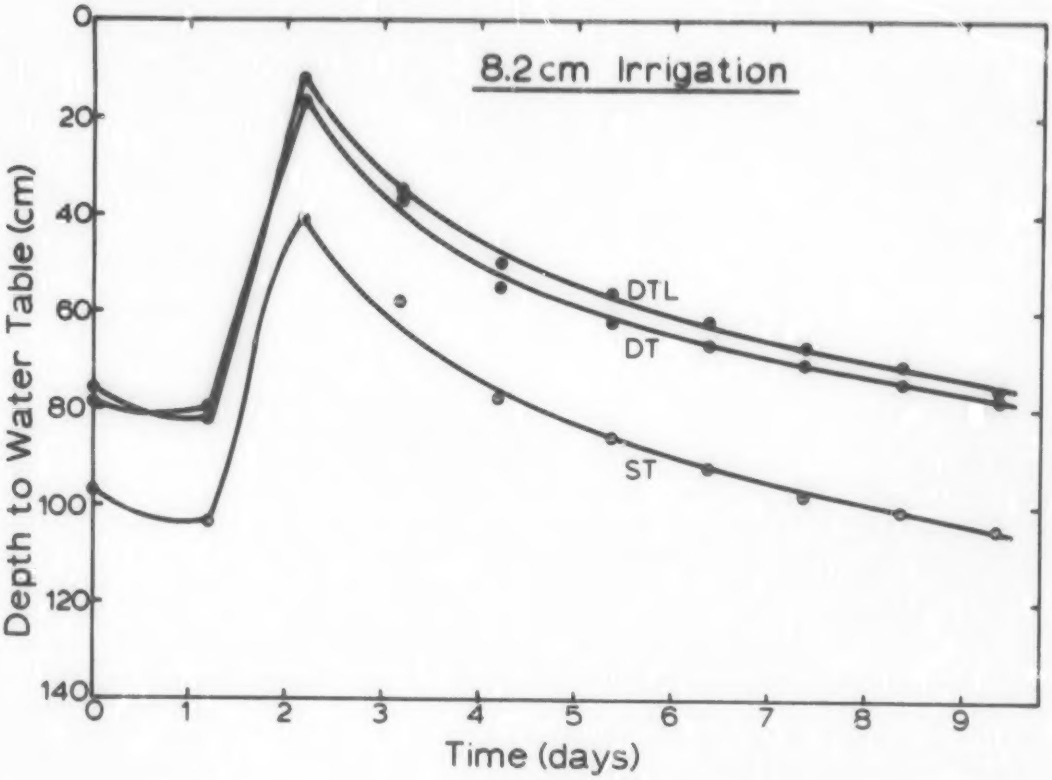


FIGURE 29. Time-dependence of water table depth measured at a point midway between two parallel drain tubes for an 8.2-cm irrigation (May 21-29, 1974) in ST, DT, and DTL plots.

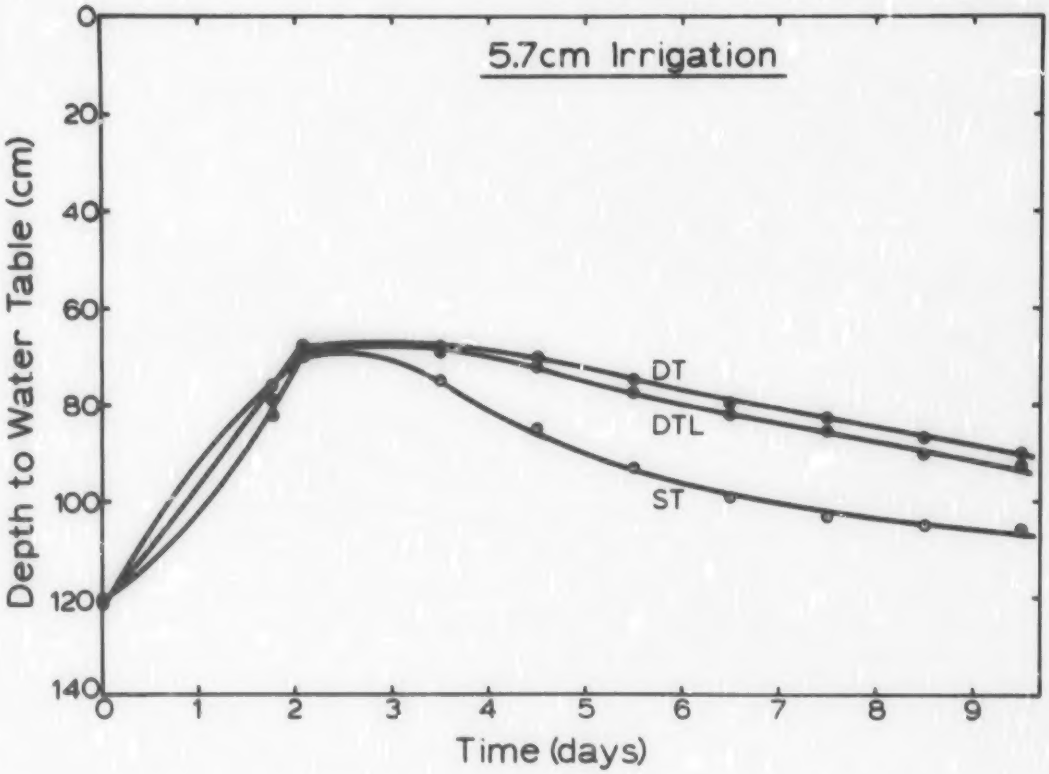


FIGURE 30. Time-dependence of water table depth measured at a point midway between two parallel drain tubes for a 5.7-cm irrigation (February 11-19, 1975) in ST, DT, and DTL plots.

in the surface soil of these profiles. Generally, water tables located at the shallowest depths at the midplane between drainage in ST, DT, and DTL treatments were associated with periods of maximum discharge of water and nutrients from subsurface drains following a rainfall event.

SUMMARY

Results indicate that drainage of the three soil management systems were greatly different. Drainage rates for subsurface drains in the ST plots were much higher than for DT and DTL plots. Deep tillage on these soils incorporated clay and organic materials from the subsoil layers into the sandy surface soil, thereby decreasing the hydraulic conductivity of the soil in the root zone. In addition to changes in the soil particle-size and pore size distributions, the drains in the DT and DTL plots appear to be partially clogged (Rogers, Simmons and Hammond, 1971). Mechanical and microbiological "clogging" of soil near drain tubes has been observed in DT and DTL plots, and the resulting hydraulic resistence to water flow decreased the drainage response of the deep-tilled plots. However, the decreased drainage characteristics of DT and DTL plots provided improved soil water storage capacities. There were also increased cation exchange capacities for the soil in the root zone which in turn resulted in larger growth rates for young citrus trees than those planted in ST plots (Calvert et al., 1976).

Following rainfall or irrigation events, hydraulic response of the ST soil was particularly rapid and of greater magnitude than for DT and DTL soils. Not only were peak flow rates for ST drains approximately 2 to 3 times greater than for other drains, but accumulative drainage of water from ST drains was also more than twice that for DT and DTL. Deep tillage appeared to decrease the magnitude of maximum subsurface drainage rates, prolong "temporary" soil water storage over very long periods of time, and resulted in slower drawdown of temporary water tables relative to that in the ST soil.

Deep tillage appeared to decrease the quantity of NO_3-N that passed through the soil and out through the drains. This decrease may be partially due to the net influence of denitrification (see Section VI) during transport of NO_3-N through the DT and DTL soils.

Although the magnitude of peak loss rates of PO_4-P from all drain lines were considerably less than for NO_3-N, the loss of PO_4-P coincided in time with those for NO_3-N. As expected, deep tillage drastically decreased leaching losses of phosphorus fertilizer. However, incorporation of lime in the deep tilled soil did not appear to greatly influence leaching of phosphorus.

These and other data suggest that the subsurface drains in this Spodosol (ST treatment) provide rapid lateral water flow and tended to reduce flow vertically through the chemically reactive, but slowly permeable spodic horizon. The subsurface drainage of the layered ST soil tended to increase leaching losses of fertilizer nutrients.

Deep tillage tended, however, to decrease subsurface drainage, increase cation exchange capacity of the top 85 cm of soil, and decrease leaching rates for NO_3-N and PO_4-P.

Hypothetical equivalent concentrations of the NO_3-N in the applied irrigation water would be 13.1, 25.6and 87.5 µg/ml for the 16.0-, 8.2-, and 2.4-cm irrigations, respectively, if the nitrate were uniformly dissolved and mixed in the applied volume of water. Considering rainfall occurred early in the 2.4 cm irrigation period, the equivalent concentration would be 39.3 µg/ml. Concentrations of NO_3-N in the drainage water from the DT plot never approached values as large as the equivalent concentration. However, NO_3-N concentrations in the drainage from ST and DTL plots after the 16-cm irrigation reached or exceeded the corresponding equivalent concentrations. After the 8.2-cm irrigation of the DTL plot, NO_3-N concentrations also reached or exceeded the corresponding equivalent concentration. The highest concentration of NO_3-N reached in the drainage water from the ST plot following the 2.4 cm irrigation was 5.3 µg/ml (Table 20).

Before peak concentrations of applied fertilizer nutrients appear in subsurface drainage water, infiltrated rain or irrigation water must flow through the surface soil displacing the soil solution through the soil profile. Powell and Kirkham (1974) showed that soluble components (example: NO_3-N) of fertilizer applied to a bedded soil with subsurface drains will move along streamlines of water flow characteristic of the given bedding geometry. For the case of drains placed beneath and parallel to each surface furrow which separate parallel beds, they found that increasing the bed slope would not only increase the volume of drainage through the soil to the drain but would also cause the soil water and accompanying solutes such as NO_3-N to move with greater velocity along comparable streamlines. Potential theory (Kirkham, Toksoz and Van Der Ploeg, 1974) for subsurface drainage of soil indicates that water infiltrating the soil surface directly above a drain has the shortest streamline or pathway to that drain. Water infiltrating the soil surface at greater distances away from the drain encounters increasingly longer pathways to the drain. Water infiltrating the soil surface near the midpoint between two parallel drains must follow the longest pathway during drainage to the drain tube sink. Thus the water flux from a subsurface drain will vary with time following an irrigation or rainfall event, and for a given amount and intensity of water applied this variation will be largely controlled by the curvilinear network of streamlines in a 2-dimensional plane normal to the axis of the drain. Also the gradients of hydraulic head and thus the water flow velocity along individual streamlines will generally be greater for the shorter streamlines. In a leaching study of salts from tile-drained saline soils, Talsma (1967) observed that during the ponded stage of irrigation removal of salt from the surface soil occurred more rapidly near the drains than midway between. After ponding, i.e. during the falling water-table stages salt was removed more evenly over the whole area. Thus, water infiltrating the soil surface at some location near the midpoint between parallel drains will generally move more slowly and follow a longer pathway to the drain than water infiltrating the soil immediately over the drain. Relatively nonreactive solutes, such as chloride, will move approximately with the same velocity along a given streamline as does the soil water; however, reactive solutes such as PO_4-P, NH_4-N and pesticides will move much slower than the water because of adsorption-desorption, chemical precipitation, microbiological tranformations (nitrification) and synthesis, and other interactions with the soil matrix. Nitrate-N is as mobile as the chloride ion but concentrations of NO_3-N which occur in the soil solution and in the drainage water are influenced by microbiological transformations between ammonium, organic and nitrate forms and denitrification which is a microbiological sink.

In response to a single irrigation or rainfall event, the drainage flux, q(t), for a parallel system of subsurface drains generally tends to increase exponentially with time to a maximum and then decrease exponentially afterwards. For steady irrigation, q(t) occurs according to the Kraijenhoff Van De Leur-Maasland equation (Wessling, 1973; Van Schilfgaarde, 1974):

$$q(t) = 0.81057R \sum_{n=1,3,5} \frac{1}{n^2} \left\{ 1 - e^{-(n^2/j)t} \right\} \qquad [1]$$

where R is the steady application rate for water, t is time, and $j = \mu S^2/\pi^2 T$ is the reservior coefficient. The parameter μ is the drainable pore space, S is the distance between drains, and T is the transmissivity of the soil (T=Kd where K is the saturated hydraulic conductivity and d is the Hooghoudt equivalent height of the drain level above an impervious soil layer). This equation describes non-steady state drainage when initially (t=0) the water table is horizontal and occurs at the drain level, when the hydraulic head always remains as zero at the drain, and when irrigation or rain occurs at a steady rate R over a time period t. This water flux as expressed by q(t) represents the overall integrated influence of soil water movement along many different streamlines. As water infiltration results in water movement downward and as the soil water pressure near the drain approaches or exceeds zero to allow flow into the drain, the inital drainage water will flow rapidly from the relatively short streamlines in the soil above the drains and with time drainage water will flow more slowly from the longer streamlines. Eventually the drainage will stop completely. Since soil water flow represents a first approximation for movement of nonreactive solutes through soils, the relative concentration C(t) of chloride or even nitrate in the drainage water for fertilized soil that receives irrigation or rainfall should approximate the exponential behaviour of the water flux, q(t). However, adsorption-desorption and other interactions will result in a retardation or lag with time for movement of reactive solutes such as PO_4-P, 2,4-D, and terbacil relative to water flow. Thus, magnitudes of relative concentrations for solutes such as PO_4-P in drainage water should be low relative to an inert ion like Cl. The Cl should also appear in the drainage water prior to that for the PO_4-P.

Because of the large volume (3-dimensions) of soil drained by a given length of subsurface drain, concentrations of solutes in the drainage water would not be expected to undergo drastic changes over short time periods (hours and days). Relatively long periods with nearly constant concentration of NO_3-N were in fact observed in drainage water from ST and DTL plots following the 8.2- and 16.0-cm irrigations, and to some extent following the 2.4-cm irrigation for the ST plot. Also, a reasonably consistent quantity of water was observed to flow from the drains of the ST plot before the peak NO_3-N concentration was reached. The exact quantities of water were 2.74, 3.57, and 2.41 cm, respectively, for the 16.0-, 8.2-, and 2.4-cm irrigations.

The higher concentrations of nutrients observed in the drainage water after fertilization contrasts with the low concentrations, nearly zero, observed in water from the Control plot during identical time periods. The higher overall nutrient content from the grove area would confirm that the agricultural practice of fertilization does increase nitrogen and phosphorus nutrient concentrations in the water. However, the lower concentrations in the perimeter ditch and at the South Sump shows that these nutrients are reduced significantly before being discharged into the drainage canals administered by the North St. Lucie River Water Management District and the Central and Southern Florida Flood Control District.

Thus the DT and DTL soil management treatments with combined subsurface drainage and deep tillage appeared to offer the advantages of (1) greater capacity to retain infiltrated water against drainage loss, (2) greater capacity to attenuate loss of applied fertilizer nutrients and pesticides with drainage water, (3) providing a "buffering capacity" against very fast rates of water table rise during rainy periods, but increasing surface runoff over surface tilled and (4) permitting the maintenance of an aerobic, unsaturated root zone which has a large capacity to attenuate leaching losses of nitrogen and phosphorus and thus minimize pollution of nearby drainage canals. A practical disadvantage of the deep tillage management is the high cost relative to the shallow tillage management.

SECTION V

CONCENTRATIONS AND FLUX OF CHLOROBENZILATE ACARICIDE AND TERBACIL AND 2,4-DICHLOROPHENOXYACETIC ACID HERBICIDES IN SURFACE AND SUBSURFACE DRAINAGE WATER FROM A CITRUS GROVE

EXPERIMENTAL METHODS AND PROCEDURE

Three pesticides - chlorobenzilate (acaricide), 2,4-Dichlorophenoxyacetic acid (herbicide), and terbacil (herbicide) - were applied routinely to the ST, DT, and DTL soil management plots of the SWAP citrus grove with application rates (Table 23) of 1.4, 3.7, and 4.5 kg/ha, respectively, for the three chemicals. Chemical structures for these materials are given in Fig. 31. The chlorobenzilate was applied as an aqueous spray directly to the citrus trees, whereas the terbacil was applied in aqueous spray to a 3-meter swath of soil along the rows of citrus. The 2,4-D was applied in aqueous spray over a 1-meter swath of soil along the midsection between the two rows of trees along the top of each bed. Since the tree rows were perpendicular to subsurface drain tubes, applications of these pesticides were in bands which were also perpendicular to the drains.

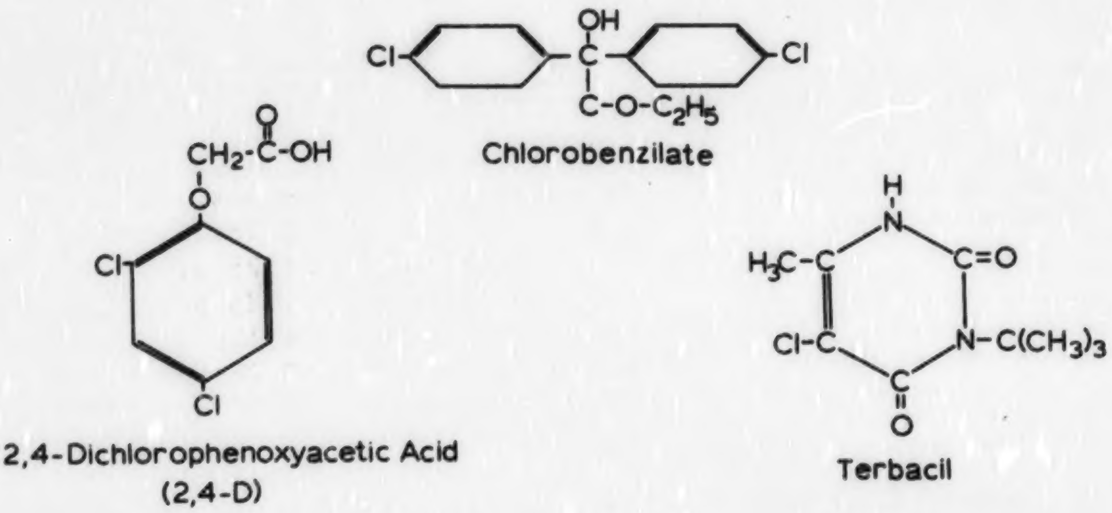
Table 23. Dates and quantities of 2,4-D, terbacil, and chlorobenzilate applied to ST, DT and DTL experimental plots.

Date	Pesticide	Application Rate
August 21-22, 1973	terbacil	4 lbs. active/acre
January 17-18, 1974	chlorobenzilate	1.25 pts./500 gal.
March 4, 1974	terbacil	4 lbs. active/acre
March 4, 1974	2,4-D	3 lbs./acre
March 4, 1974	chlorobenzilate	1.25 pts./500 gal.
May 20, 1974	chlorobenzilate	1.25 pts./500 gal.
May 21-24, 1974	terbacil	4 lbs. active/acre
May 21-24, 1974	2,4-D	3 lbs. active/acre
July 10-11, 1974	chlorobenzilate	1.25 pts./500 gal.
March 11-13, 1975	terbacil	4 lbs. active/acre
March 11-13, 1975	2,4-D	2 lbs./100 gal.
March 11-13, 1975	chlorobenzilate	2.5 pts./500 gal.

Following applications of these pesticides, samples of subsurface drainage and surface runoff waters were taken at selected times, frozen, and shipped to the Pesticide Research Laboratory in Gainesville for analyses. Irrigation was sometimes used to initiate subsurface drainage, and all other periods of drainage were attributed to rainfall. Sample size was approximately 100 ml of water.

Water samples were analyzed for concentrations of terbacil and chlorobenzilate using the method of Pease (1966) and Wheeler et al. (1971) with added modifications. THese changes included: (1) filtration of water samples to remove suspended materials, (2) adjustment of sample pH to 3-4 with addition of HCl acid, (3) two extractions of the acidified sample using 100 ml volumes of ethyl acetate, and (4) concentration of the ethyl acetate extract to provide an appropriate volume for analysis by gas chromatography.

An unpublished method by H. A. Moye was used to determine concentrations of 2,4-D herbicide as the butoxy ethyl ester in water samples. Each water sample was first extracted for 2,4-D using ethyl acetate, the same procedure followed for chlorobenzilate and terbacil extraction. The next step was to evaporate the ethyl acetate solution to dryness in a test tube using a gentle stream of dry nitrogen gas. Preparation of the butoxy ethyl ester derivative was as follows: (1) 5 ml of acetyl chloride was added dropwise to cold butoxyethanol (the final volume was 100 ml). (2) One tenth ml of this solution was then added to the test tube containing the extracted 2,4-D. The tube was sealed and held at 80°C for 30 minutes. (3) The tube was cooled and 2.0 ml of hexane added to the tube. (4) The hexane solution was then extracted three times with 0.2 $\underline{M}$ K_2HPO_4 (the K_2HPO_4 was discarded). (5) A small amount of anhydrous sodium sulfate was then added to the solution to dry the sample. Gas chromatography was then used to determine the sample concentration of 2,4-D.



Chlorobenzilate

2,4-Dichlorophenoxyacetic Acid
(2,4-D)

Terbacil

FIGURE 31. Structural formulas for chlorobenzilate, 2,4-D, and terbacil pesticides.

Average recoveries of terbacil, chlorobenzilate, and 2,4-D from water samples fortified with known concentrations were 80, 83, and 85%, respectively, when these analytical methods were followed.

Soil samples were removed, extracted, and analyzed for terbacil, chlorobenzilate, and 2,4-D content. An analytical procedure by Jollifee et al. (1967) was used to determine contents for terbacil and 2,4-D. Chlorobenzilate analyses were performed using the method of Wheeler et al. (1969).

Operating parameters for the gas chromatographic analysis of extracts from water and soil samples were as follows: Temperatures for the glass column, injector and tritium electron-capture detector were 185°, 225°, and 210°C, respectively; the column was 183 cm long with 4 mm inside diameter and was packed with 3% QF-1 on 80/100 mesh Gas Chrom Q (Applied Science). The flow rate for the nitrogen carrier gas was 85 ml/min.

RESULTS AND DISCUSSION

Concentrations (ppb or μg/l) of terbacil and 2,4-D in subsurface drainage waters from submerged and open outlet drains in ST, DT, and DTL soil management plots are presented in Figs. 32-35 for the first 67 days following applications of terbacil, 2,4-D and chlorobenzilate on March 5, 1974.

A 16.0 cm irrigation was applied (over a 39 hour period) on March 6 and a total of 2.41 cm of rain occurred on March 14 and 15. Concentrations of terbacil were always less than 130 μg/l in drainage water, from all three plots and concentrations of 2,4-D did not exceed 80 μg/ml. Chlorobenzilate was not detected in the drainage waters at any time. Concentrations of 2,4-D in drainage waters from ST and DT plots were always less than 25 μg/l and did not vary greatly between drain lines with open outlets and submerged outlets. Concentrations of 2,4-D in drainage water from the submerged DTL drain were lower (maximum of 75 μg/l) in water from drains with open outlets. Earlier, Calvert and Phung (1971) observed that concentrations of NO_3-N in water from drains with submerged outlets from ST, DT, and DTL were generally less than in drains with open outlets. They explained this difference in NO_3-N concentration by possible loss of N by denitrification in the water-saturated soil above the drains with submerged outlets. Phung (1971 and 1972) measured the dissolved oxygen content of drainage water from ST, DT, and DTL plots, and observed lower oxygen concentrations in water from submerged drains. Concentrations of 2,4-D and terbacil were observed to increase to broad maxima with time following the 16.0-cm irrigation. For 2,4-D, the peak concentrations then decreased with time to near zero values within 20 days after the irrigation. For ST and DT plots, the terbacil concentrations decreased after the initial peaks and then increased to form another peak later. Terbacil concentrations in drainage water from the DTL drains decreased very slowly from the initial build-up of the peak. The relative elution patterns for terbacil were essentially the same in water from open and submerged drains.

Drainage water flux (flow rate), concentrations of terbacil and 2,4-D and flux of terbacil and 2,4-D in water from submerged and open outlet drains in ST, DT and DTL plots are presented in Figs. 36-47 for the first

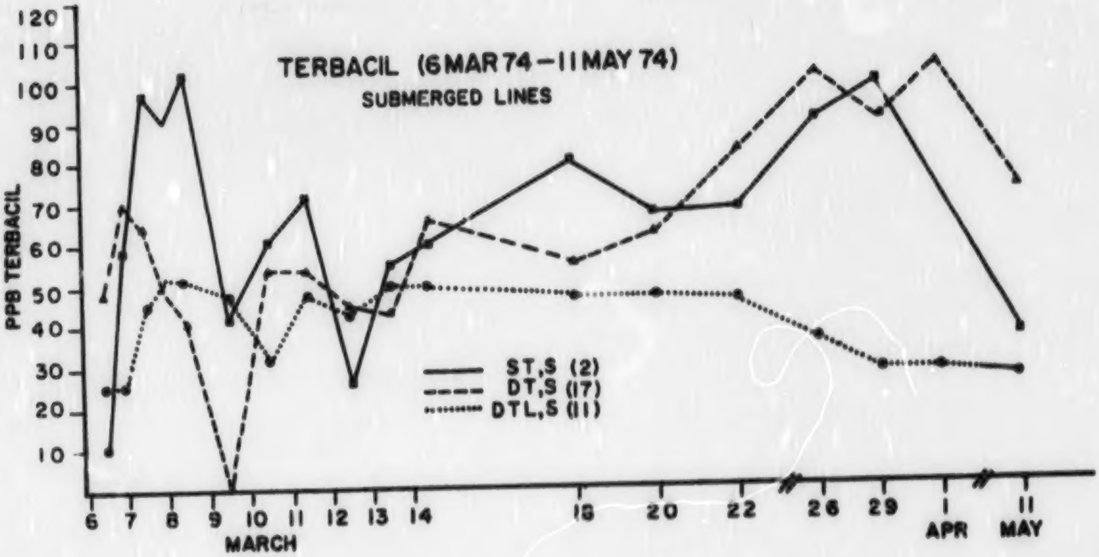


FIGURE 32. Terbacil concentrations in water from submerged drains in ST, DT, and DTL plots during the period March 6 to May 11, 1974.

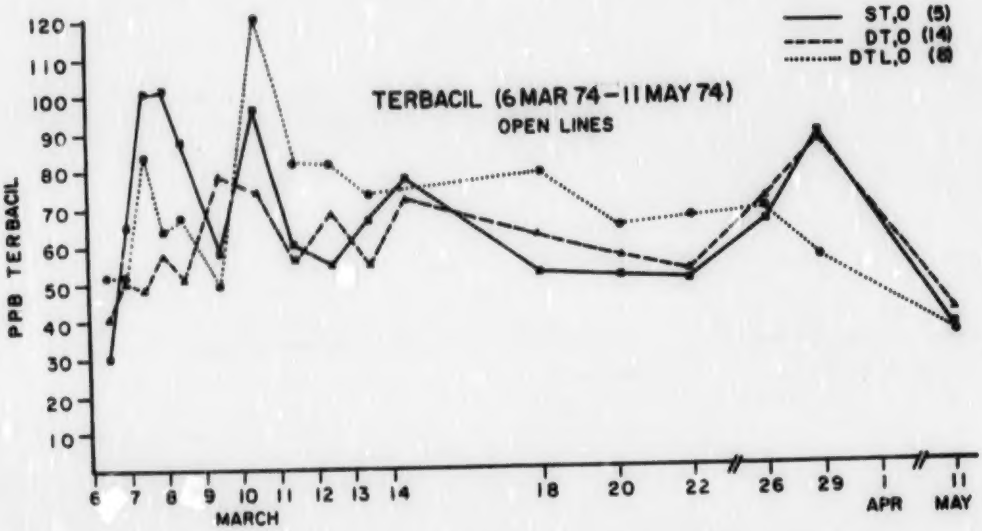


FIGURE 33. Terbacil concentration in water from open drains in ST, DT, and DTL plots during the period March 6 to May 11, 1974.

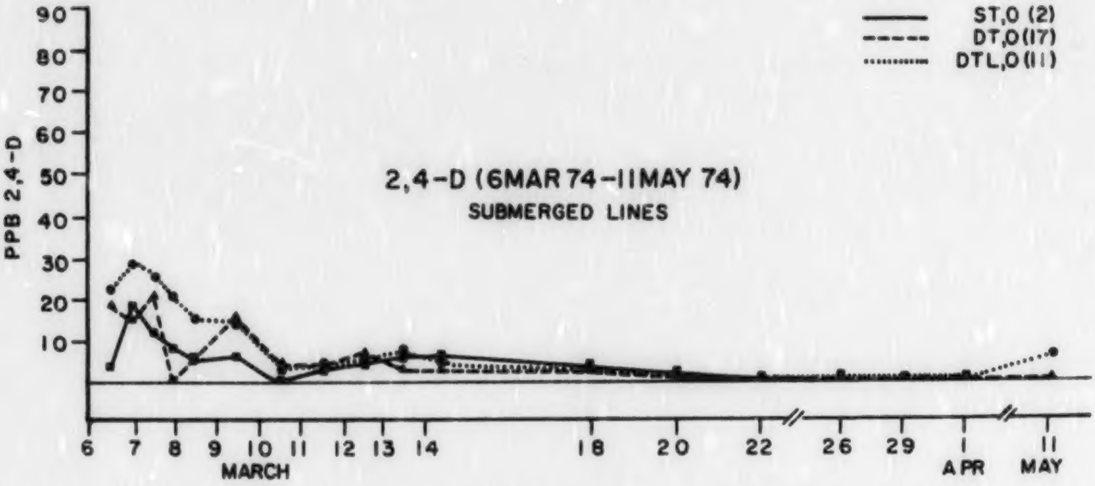


FIGURE 34. Concentrations of 2,4-D in water from submerged drains in ST, DT, and DTL plots during the period March 6 to May 11, 1974.

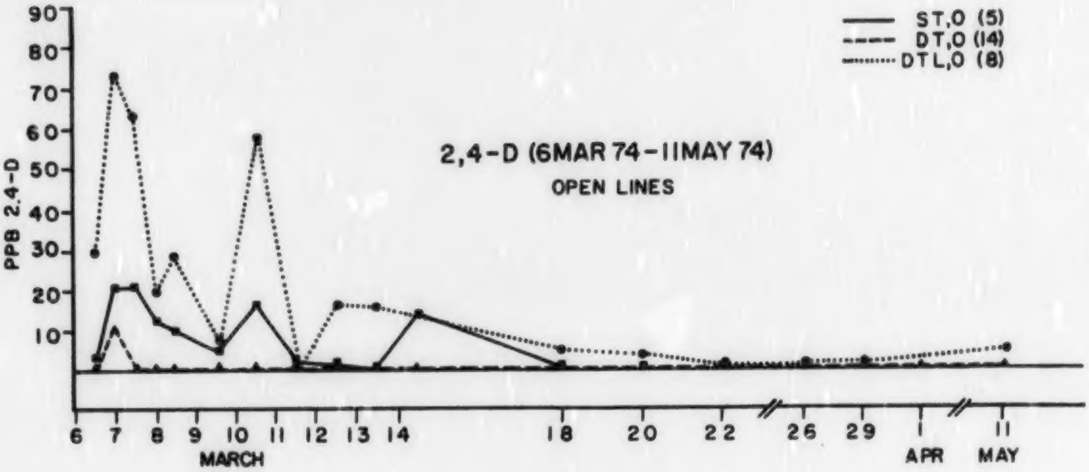


FIGURE 35. Concentrations of 2,4-D in water from open drains in ST, DT, and DTL plots during the period March 6 to May 11, 1974.

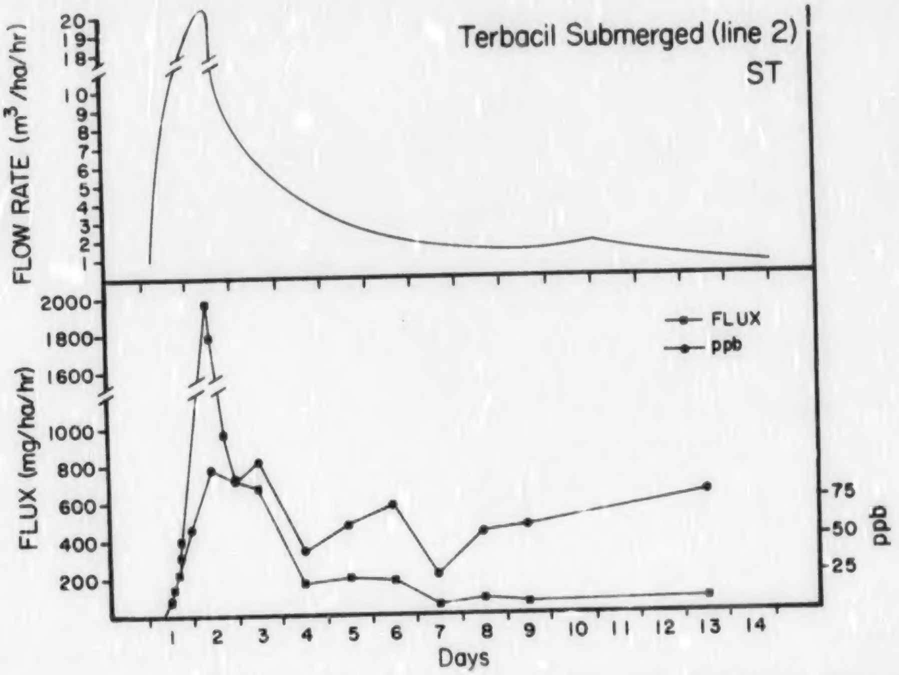


FIGURE 36. Water flux, terbacil concentration, and terbacil flux in water from a submerged drain in the ST plot during a 14-day period (March 6-19, 1974) following a 16.0-cm irrigation.

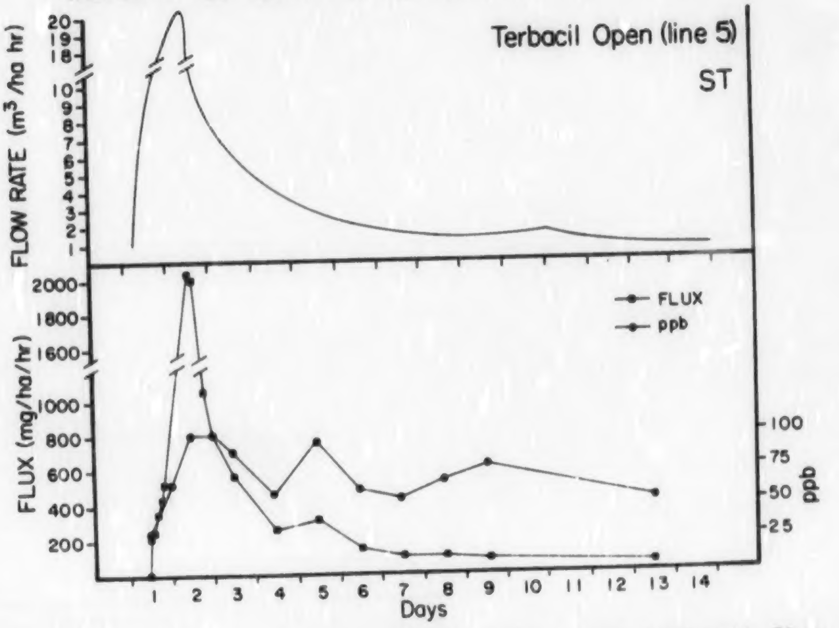


FIGURE 37. Water flux, terbacil concentration, and terbacil flux in water from an open drain in ST plot during a 14-day period (March 6-19, 1974) following a 16.0-cm irrigation.

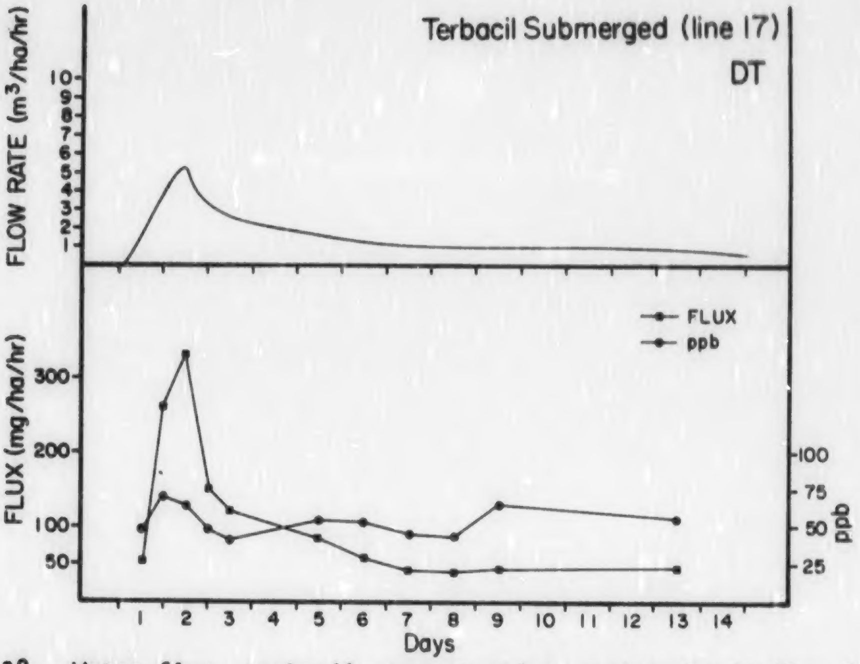


FIGURE 38. Water flux, terbacil concentration, and terbacil flux in water from a submerged drain in the DT plot during a 14-day period (March 6-19, 1974) following a 16.0 irrigation.

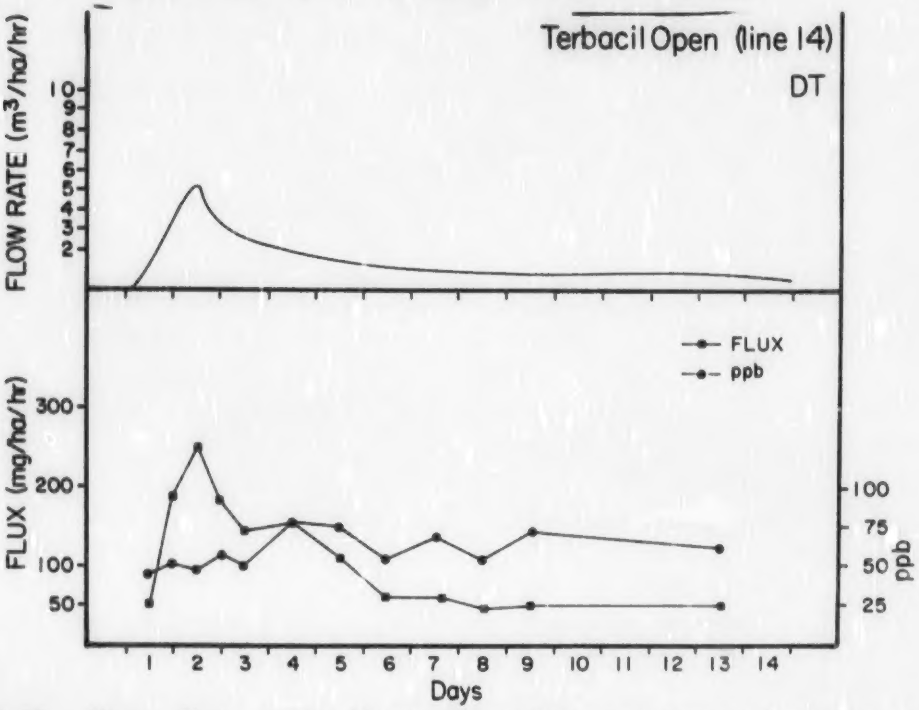


FIGURE 39. Water flux, terbacil concentration, and terbacil flux in water from an open drain in the DT plot during a 14-day period (March 6-19, 1974) following a 16.0-cm irrigation.

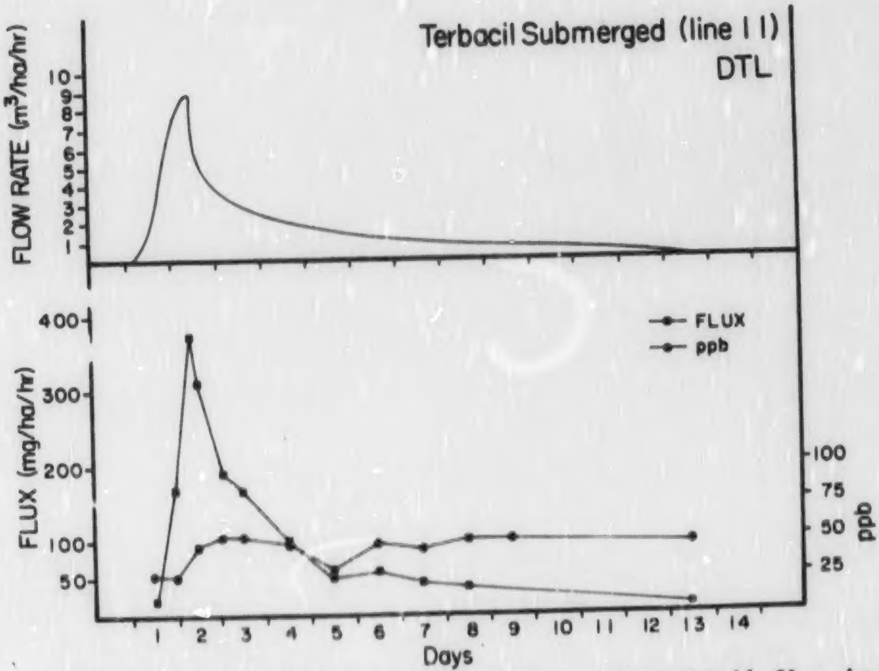


FIGURE 40. Water flux, terbacil concentration, and terbacil flux in water from a submerged drain in the DTL plot during a 14-day period (March 6-19, 1974) following a 16.0-cm irrigation.

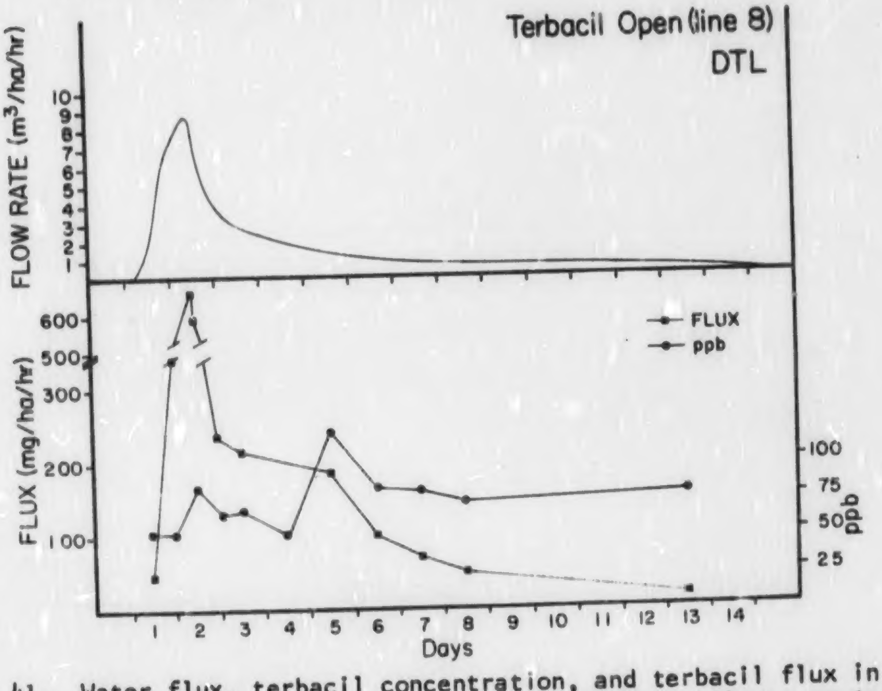


FIGURE 41. Water flux, terbacil concentration, and terbacil flux in water from an open drain in the DTL plot during a 14-day period (March 6-19, 1974) following a 16.0-cm irrigation.

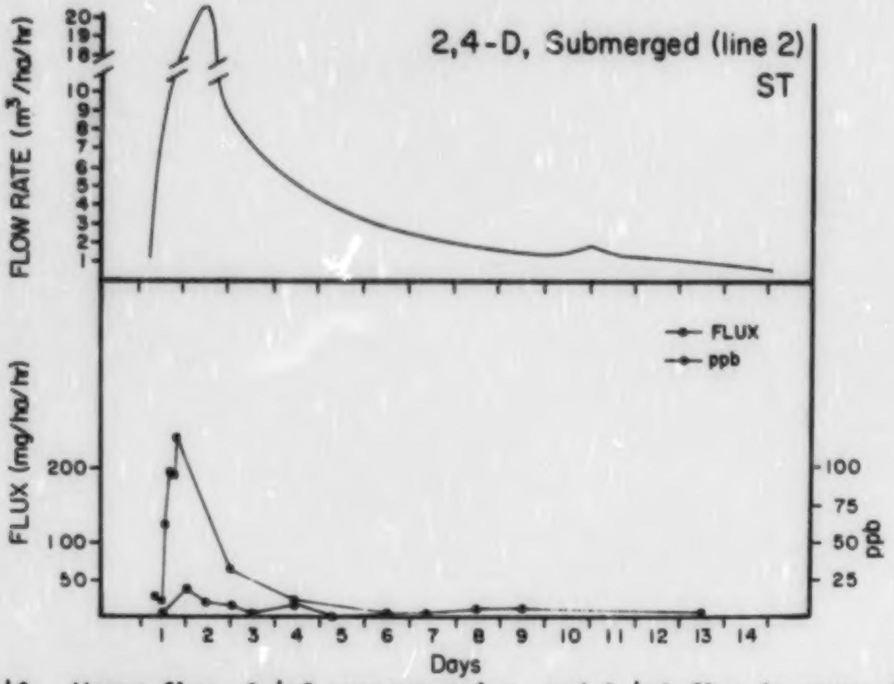


FIGURE 42. Water flux, 2,4-D concentration, and 2,4-D flux in water from a submerged drain in the ST plot during a 14-day period (March 6-19, 1974) following a 16.0-cm irrigation.

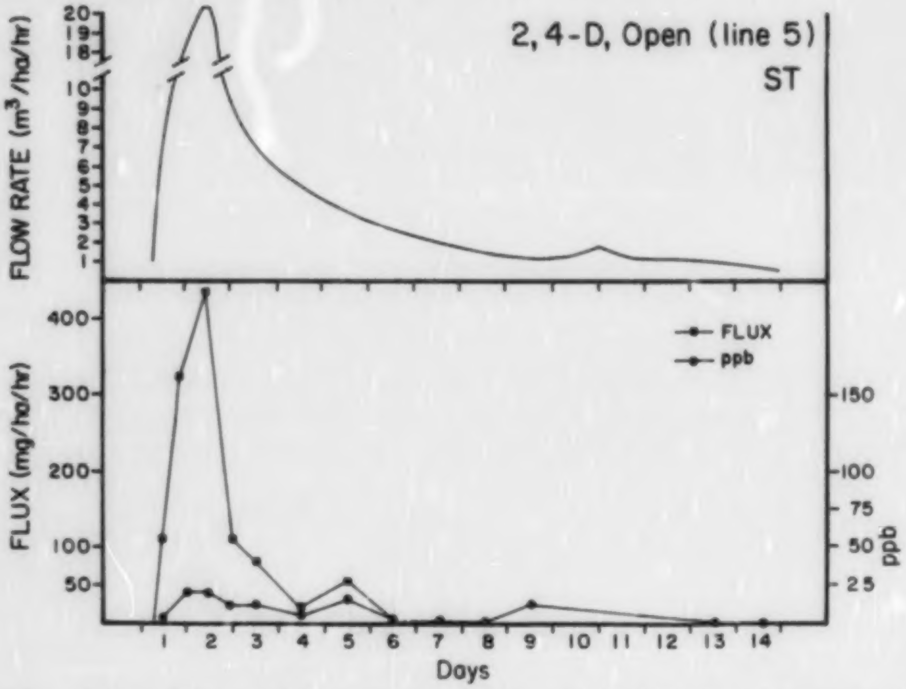


FIGURE 43. Water flux, 2,4-D concentration, and 2,4-D flux in water from an open drain in the ST plot during a 14-day period (March 6-19, 1974) following a 16.0-cm irrigation.

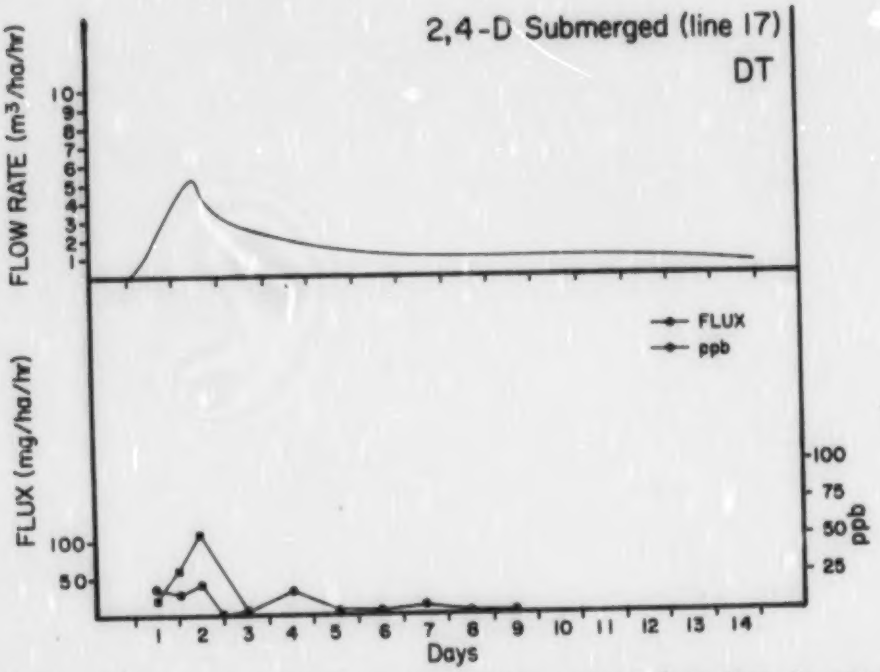


FIGURE 44. Water flux, 2,4-D concentration, and 2,4-D flux in water from a submerged drain in the DT plot during a 14-day period (March 6-19, 1974) following a 16.0-cm irrigation.

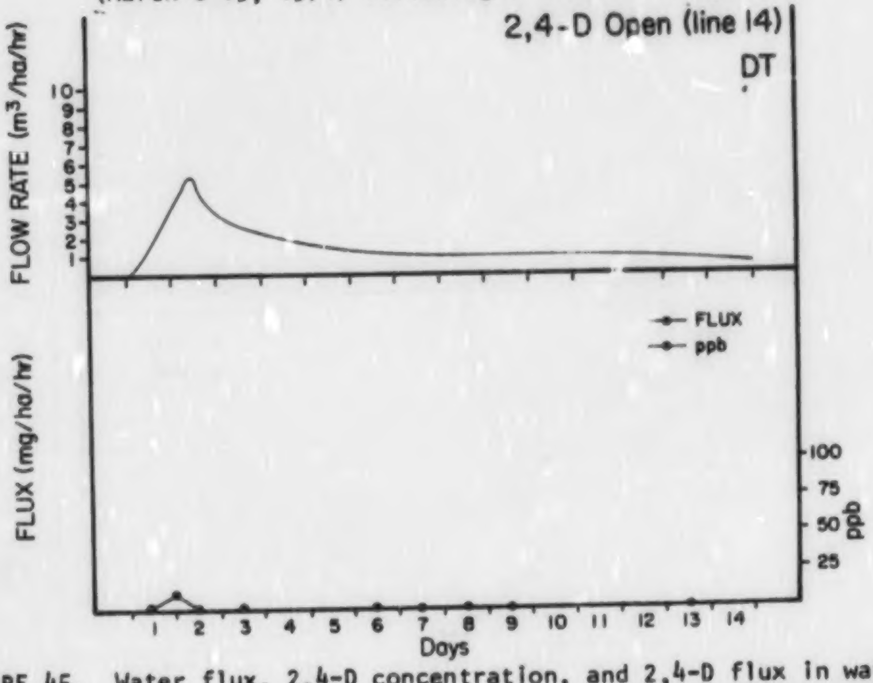


FIGURE 45. Water flux, 2,4-D concentration, and 2,4-D flux in water from an open drain in the DT plot during a 14-day period (March 6-19, 1974) following a 16.0-cm irrigation.

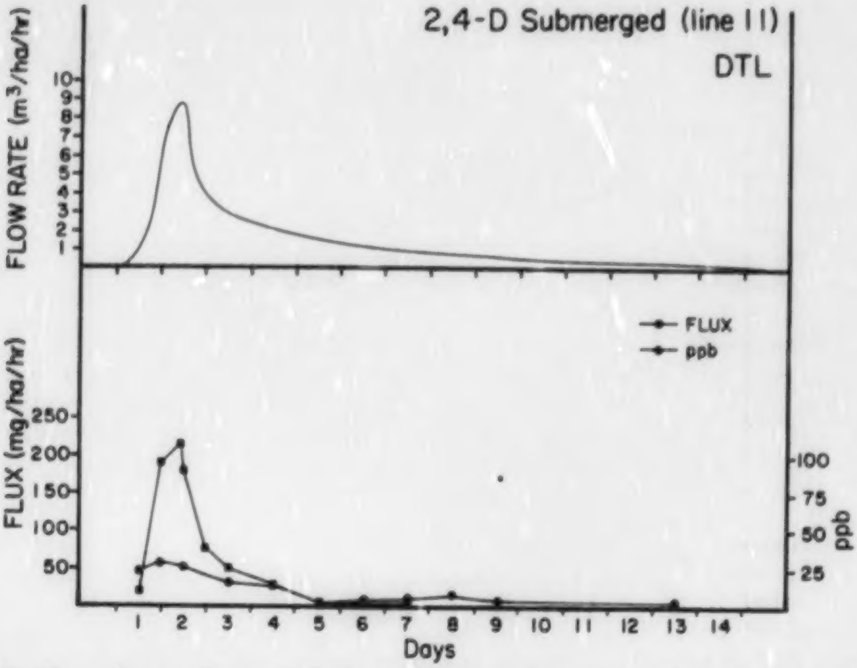


FIGURE 46. Water flux, 2,4-D concentration, and 2,4-D flux in water from a submerged drain in the DTL plot during a 14-day period (March 6-19, 1974) following a 16.0-cm irrigation.

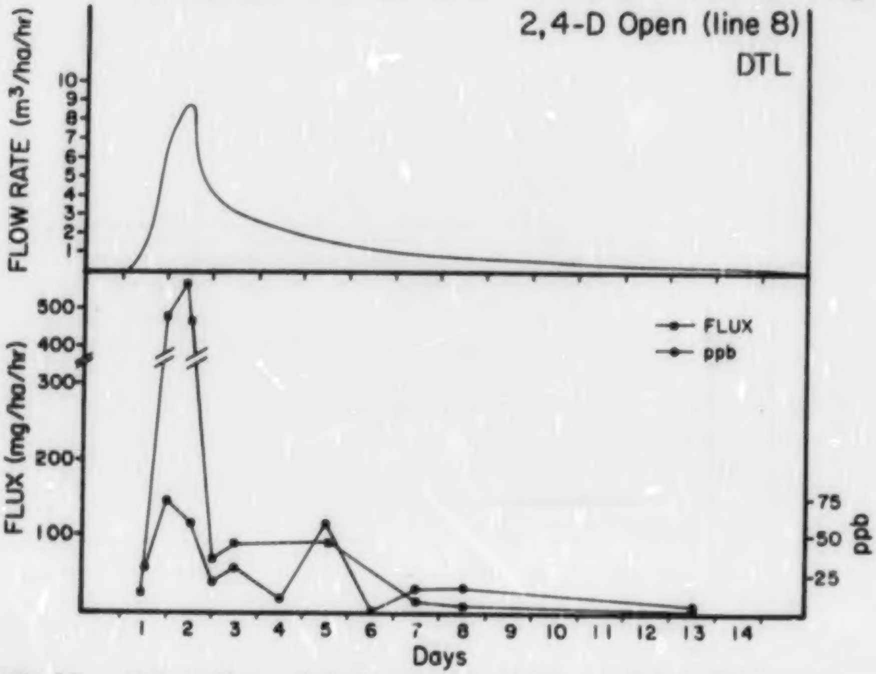


FIGURE 47. Water flux, 2,4-D concentration, and 2,4-D flux in water from an open drain in the DTL plot during a 14-day period (March 6-19, 1974) following a 16.0-cm irrigation.

14 days after the 16.0-cm irrigation on March 6. For both terbacil and 2,4-D, peak zones of flux developed with time which coincided with the times of peak water flux. Total discharges of 2,4-D and terbacil were greatest for ST drains, less from DTL, and least from DT. Concentrations of these herbicides developed very broad peak zones which decreased within about a week for 2,4-D but did not decrease during the 14-day period for terbacil. Total discharges of 2,4-D were greater in water from open outlet than from submerged drains in ST and DTL plots. Discharges of 2,4-D from the DT plot either through open or submerged drains was very small compared to that from ST or DTL. Total discharges of terbacil were not greatly different from open or submerged drains in ST, DT and DTL plots.

Concentrations of terbacil in drainage water from ST, DT and DTL soil management plots are presented in Figs. 30 and 31 for a 14-day period following an irrigation on August 22, 1973. As in the 1974 data, the concentrations reached broad maxima which were 2 to 10 days in duration. The magnitudes of the concentrations did not appear to be significantly different for open versus submerged drain outlets.

Terbacil concentrations and flux and water flux are presented in Figs. 48, 49, and 50 for drainage water from ST, DT and DTL plots during a 14-day period in March 1975 that followed a 2.4-cm irrigation. Concentrations approached peak values of about 22, 30 and 20 μg/l in drainage from ST, DT and DTL submerged drains, respectively.

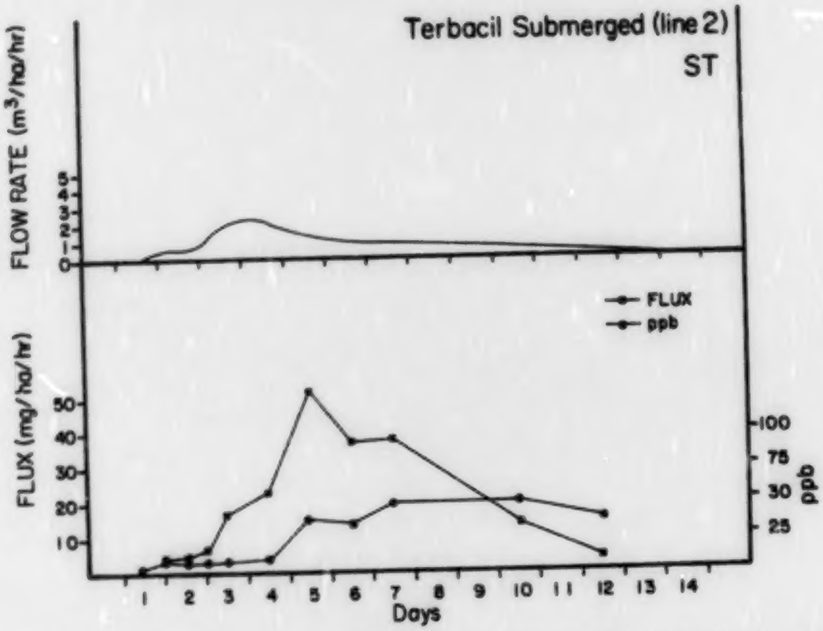


FIGURE 48. Water flux, terbacil concentration, and terbacil flux in water from a submerged drain in the ST plot during a 14-day period (March 17-31, 1975) following a 2.4-cm irrigation.

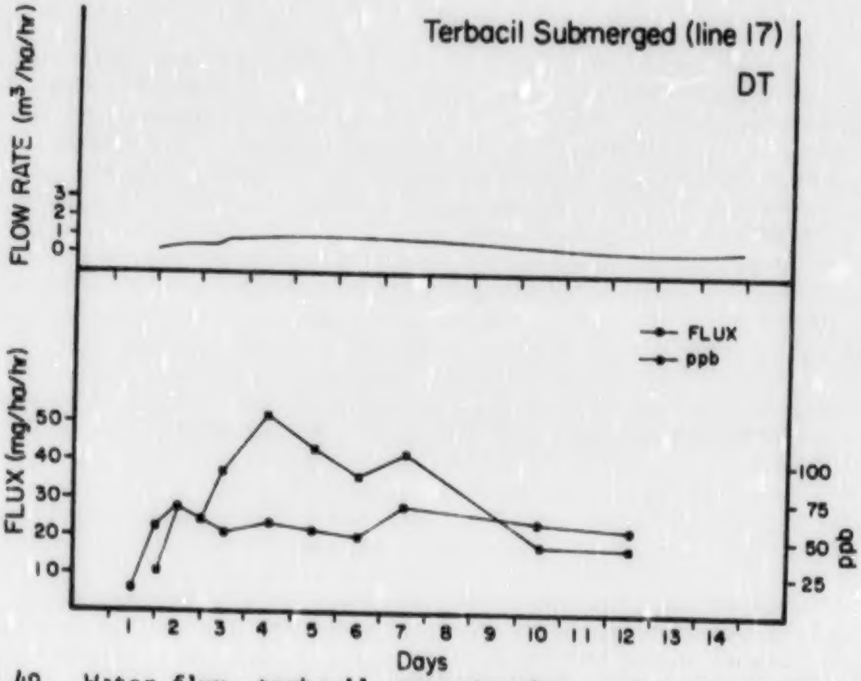


FIGURE 49. Water flux, terbacil concentration, and terbacil flux in water from a submerged drain in the DT plot during a 14-day period (March 17-31, 1975) following a 2.4-cm irrigation.

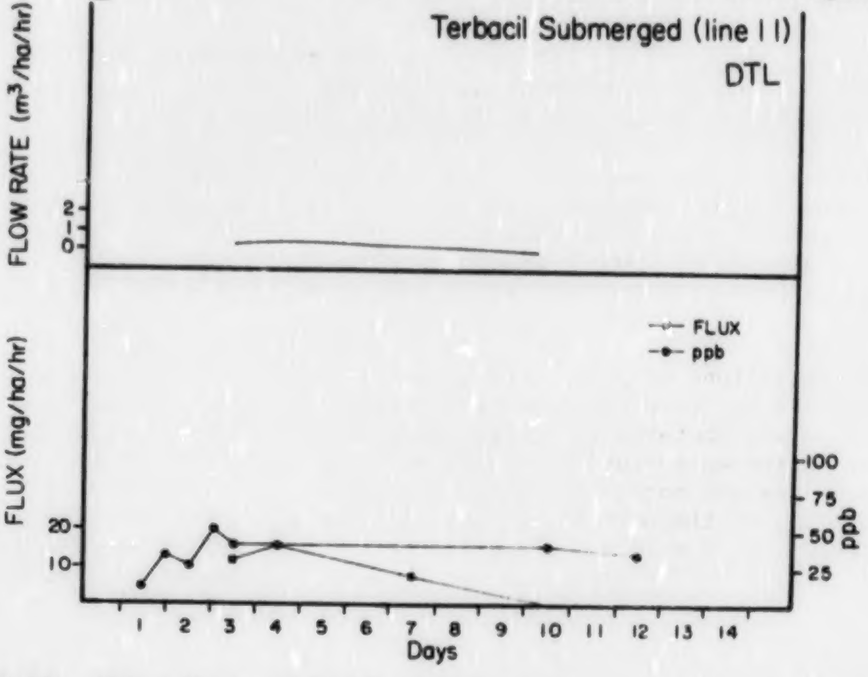


FIGURE 50. Water flux, terbacil concentration, and terbacil flux in water from a submerged drain in the DTL plot during a 14-day period (March 17-31, 1975) following a 2.4-cm irrigation.

In Fig. 51, the amounts of terbacil discharged within 14-day periods following 16.0- and 2.4-cm irrigations (Table 24) are plotted versus the sum of rainfall and irrigation. For the 2.4 cm irrigation terbacil discharge was approximately the same for ST, DT and DTL plots; however, for the 16-cm irrigation the amount of terbacil discharged was several fold larger for the ST treatment than either DT or DTL. Data shown in Fig. 51 is for drains with submerged outlets only. For the 16.0-cm irrigation in 1974, terbacil discharge from open drains was only slightly greater than from submerged drains; however, 2,4-D discharge from open drains was 2 to 3 times greater than from submerged drains.

SUMMARY

Concentrations of terbacil and 2,4-D in the range of 0-130 ppb (μg/l) were observed in subsurface drainage waters from ST, DT and DTL soil management plots during the first few weeks following application of these herbicides to the soil surface. These results were in agreement with earlier laboratory work (Mansell et al., 1971) which showed that aqueous solutions with 1000 μg/l of terbacil could be miscibly displaced through water-saturated columns of Wabasso sand. For the surface soil (0-10 cm profile depth) peak terbacil concentrations were approximately 200 μg/l and occurred about 0.5 pore volumes after the peak concentrations occurred for applied Cl; whereas for the subsurface (33-76 cm profile depth) soil, peak terbacil concentrations were 800 μg/l and occurred at the same time as did the Cl peak. In that same work, acarol which is a chemical analogue of chlorobenzilate moved very little during miscible displacement through the surface and subsurface Wabasso soil. In this research, chlorobenzilate was not observed in subsurface drainage water from ST, DT and DTL soils (Table 25). A single application of terbacil in 1974, however, was observed to increase the contents of terbacil in the soil by 856, 833, and 995 μg/kg.

Discharge of terbacil and 2,4-D in subsurface drainage water followed closely the flux of water from the drains. Relatively large water fluxes were observed from the ST plot and thus the herbicide fluxes were greater from ST drains than from DT and DTL drains. Thus deep-tillage appeared to decrease losses of terbacil and 2,4-D in drainage water from this Spodosol.

Concentrations of 2,4-D were generally higher in drains with open outlets relative to those for submerged drains. This difference in concentration may be attributable to greater microbiological degradation of the 2,4-D molecule in the water-saturated soil near the submerged drains. Terbacil concentrations did not differ greatly between water from open and submerged drains. Some of the half-lives reported (Table 27) for 2,4-D, terbacil, and chlorobenzilate in soil are approximately 3-14, 150-225, and 21 days, respectively. Hamaker (1972) reported characteristic times of 17 days for 2,4-D and 184 days for terbacil as time required for 50% of applied chemical to disappear from a soil.

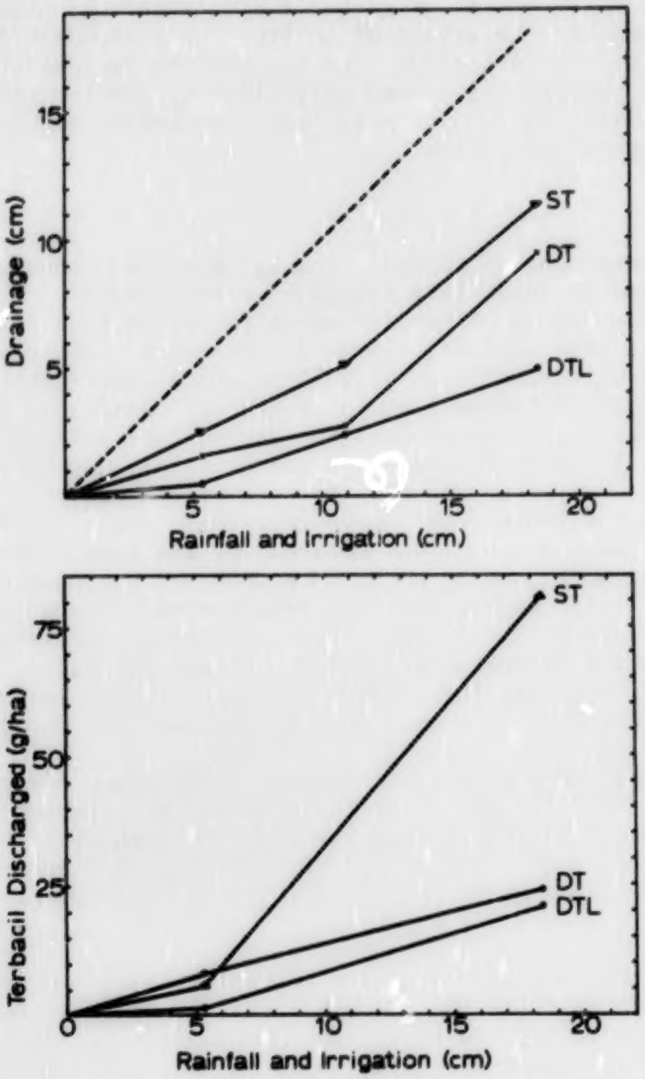


FIGURE 51. Quantities of subsurface drainage and terbacil discharged with drainage water versus the amounts of rainfall plus irrigation received for 14-day periods following irrigation of ST, DT, and DTL soil management plots.

Table 24. Quantities of 2,4-D and terbacil pesticides discharged in subsurface drainage waters from ST, DT, and DTL soil management plots during 14-day periods following an irrigation of 16.0 cm (plus 2.41 cm of rain) during March 16-19, 1974 and 2.4 cm (plus 2.93 cm of rain) during March 17-31, 1975. Data is presented for subsurface drains with open and submerged outlets.

		2,4-D Discharged			Terbacil Discharged		
Date	Drain Outlet	ST	DT	DTL	ST	DT	DTL
		------(g/ha)------			------(g/ha)--------		
1974	open	15.26	none	20.55	82.72	26.88	37.08
1974	submerged	7.66	3.19	8.81	80.94	24.19	20.81
1975	submerged	---	----	---	5.91	7.94	1.49

Table 25. Concentrations (μg/kg) of terbacil and chlorobenzilate pesticides in ST, DT and DTL surface soil prior to and immediately following an application of these chemicals.

	Terbacil			Chlorobenzilate		
Date	ST	DT	DTL	ST	DT	DTL
		(μg/kg)			(μg/kg)	
February 29, 1974	558	117	146	0	0	0
March 4, 1974	1,414	950	1,141	0	0	0
Increase	856	833	955	0	0	0

Table 26. Total quantities of terbacil and 2,4-D discharged in subsurface drainage water from ST, DT and DTL plots during 14-day periods following sequences of herbicide application and irrigation. Discharges were measured from single drain tubes which each drained areas of approximately 0.1673 hectares.

Period Sampled	Soil Treatment	Pesticide	Quantity of pesticide discharged (g/ha)
March 17-31, 1975	ST	Terbacil (submerged*)	35.3
	DT	Terbacil (submerged)	47.5
	DTL	Terbacil (submerged)	8.9
March 6-19, 1974	ST	Terbacil (submerged)	483.9
		Terbacil (open**)	494.5
	DT	Terbacil (submerged)	144.6
		Terbacil (open)	159.5
	DTL	Terbacil (submerged)	124.4
		Terbacil (open)	221.7
	ST	2,4-D (submerged)	45.8
		2,4-D (open)	91.2
	DT	2,4-D (submerged)	19.1
		2,4-D (open)	0
	DTL	2,4-D (submerged)	52.7
		2,4-D (open)	122.9

* Outlet for drain tube was submerged

** Outlet for drain tube was open.

Table 27. Half-lives for chlorobenzilate, terbacil, and 2,4-D pesticides incubated in several soil substrates.

Chemical	Substrate	Half-life	Reference
2,4-D	soil (30°C)	3 days	Haque and Freed (1974)
2,4-D	soil that has been treated with 2,4-D for several years	10-14 days	Hassall (1969)
Chlorobenzilate	soil (Leon and Lakeland sands)	21 days	Wheeler et al (1973)
Terbacil	soil (15°C)	225 days	Haque and Freed (1974)
Terbacil	soil (30°C)	150 days	Haque and Freed (1974)

SECTION VI

DENITRIFICATION IN SHALLOW- AND DEEP-TILLED SPODOSOL

EXPERIMENTAL METHODS AND PROCEDURES

The denitrification potential for the 3 tillage treatments - ST, DT and DTL - was investigated to help explain the observed differences in nitrate loss in drainage water from these treatments. Denitrification as used herein is the microbiological conversion of the NO_3-N ion to nitrogen gases, primarily N_2O and N_2 and possibly NH_3. This conversion occurs only in the absence of O_2 and in the presence of a readily available source of energy (Stanford et al., 1975) for the facultative microorganisms mediating these reactions. Such conditions are usually associated with water-saturated soil, but sometimes may occur in micro-environments within a well-drained soil. Thus denitrification may occur in a macroscopically or seemingly aerobic soil.

The redox potential (Eh) of a soil can be used as a qualitative indicator of the type of reactions occurring within a soil since redox reactions usually occur sequentially (Ponnamperuma, 1972). When the level of soil oxygen is depleted to very low values, nitrate becomes an electron acceptor in these reactions rather than oxygen.

At a pH of 7, denitrification begins at an Eh of approximately +200 mv. The Nernst equation indicates that each decrease in pH of 1 unit should increase the redox potential by 59 mv; therefore, at pH 5 denitrification should begin at about +318 mv. In reality the dependence of Eh upon pH varies considerably and for the normal range of soil pH, i.e., pH 5 to 7, denitrification occurs in the Eh range of +200 to +350 mv.

Ponnamperuma (1972) states that disappearance of NO_3-N in flooded soil usually follows first-order kinetics, which means that the rate of denitrification depends upon the concentration of nitrate. Rates of denitrification were also stated to be greater in nearly neutral soils than in acid soils. Stanford et al. (1975) measured denitrification rates for 30 soils which differed widely in pH, organic C contents, texture, etc. They reported apparent first-order rate constants (denoting the fractional loss of NO_3-N per hour) ranging from 0.001 to 0.040 hr^{-1}. The rate constants increased with increasing levels of extractable soil carbon.

A laboratory study to determine the effect of tillage treatment on denitrification potential of soil from the experimental site was conducted. Soil samples were taken from profiles of ST, DT and DTL treatments to a depth of 90 cm. Selected characteristics of the soil samples are given in Table 28. Eighty-five grams of soil and 25 ml of a 50 µg/ml NO_3-N solution were placed in a 75 ml jar. After flushing the air in the jar with inert He gas, the jar was sealed and incubated anaerobically for periods ranging from 3 to 25 days. At selected times, redox potential and pH measurements were made. Redox potentials were obtained using a platinum electrode. Electrodes were slowly moved about in the sample during measurement and minimum readings were recorded. The sample was then stirred under N_2 gas and an average Eh was taken. Each sample was then filtered and the filtrate analyzed for NO_3-N. Nitrate disappearance was attributed to denitrification.

Table 28: Physical and chemical characteristics of ST, DT, and DTL soil samples from the SWAP citrus grove.

Soil Treatment	Sample Depth	pH	Organic Matter
	--cm--		---%---
ST	0-30	4.6	1.68
	30-66	4.2	0.31
	66-81	4.3	0.22
	81-90(Spodic)	4.5	2.64
DT	0-30	4.5	2.64
	30-60	3.9	1.21
	60-90	4.2	1.39
DTL	0-30	5.7	1.67
	30-60	5.6	1.69
	30-90	5.8	1.60

During the intensive sampling periods of March and May, 1974, Eh measurements were made on the tile drainage water and in the soil profile. Water samples were taken from the tile line in a 100 ml container and Eh was read immediately using a portable pH meter with a millivolt readout and a combination pt electrode. Soil Eh values were obtained by placing constructed Pt electrodes (18 gauge Pt wire fused to 12 gauge copper wire) at several depths in the soil profile during the sampling period.

RESULTS AND DISCUSSION

In the laboratory study, redox potentials of the surface (0-30 cm) sample from ST (Table 29) showed soil microenvironments capable of supporting denitrification developing within 3 days and persisting throughout the experiment. Redox potentials of the microenvironments are characterized by the minimum Eh values. Nitrate in the surface horizon was essentially depleted by the end of the experiment (Fig. 52). In contrast, little

Table 29: Redox potentials observed during anaerobic incubation of the ST soil samples.

Depth	Time, Days										
	0	3		6		9		19		25	
		avg.	min.	avg.	min.	avg.	min.	avg.	min.	avg.	min.
--cm--	mv										
0-30	520	445	185	465	165	408	70	335	105	360	195
30-66	570	545	305	525	465	470	105	435	135	470	155
66-81	585	605	605	605	535	640	585	485	485	645	595
81-90	490	405	375	505	425	458	365	435	355	455	390

depletion of NO_3-N occurred in the lower horizons, likely due to a lack of an energy source as suggested by the low organic matter contents of the 30-66 and 66-80 cm samples. The lower NO_3-N concentrations noted in the Spodic samples were due to dilution of the NO_3-N solution by the high initial moisture content of this sample. Even though the spodic layer sample contained more organic matter than the overlying material, this organic matter is apparently not in a readily available form (Phung, 1972).

Mixing of the soil profile in DT and DTL plots resulted in a redistribution of the organic matter throughout the top 90 cm of the soil profile. Redox potentials of DT samples decreased to below +350 mv at all depths but the lowest values were obtained in the surface sample (Table 30). For soil sampled at equivalent depths, redox potentials of DTL samples (Table 31) were lower than for DT samples. Nitrate disappearance (denitrification)

Table 30: Redox potentials observed during anaerobic incubation of the DT soil samples.

Depth	Time, Days										
	0	3		6		9		19		25	
		avg.	min.	avg.	min.	avg.	min.	avg.	min.	avg.	min.
--cm--	mv										
0-30	555	405	165	495	245	465	315	435	105	445	125
30-60	605	495	385	455	235	522	115	465	205	510	225
60-90	605	445	225	485	305	---	---	455	335	500	27

occurred at all depths in the mixed profiles (DT and DTL) but at a much slower rate than in the ST surface horizon (Figs. 52-54). Also, denitrification occurred at a faster rate in the DTL samples than in the DT samples. At this point it is not known whether this difference was due to greater organic content or lower acidity in DTL due to liming. Rates of denitrification obtained for the surface horizon of ST and an average of the 3 depths in DT and DTL were 2.24, 0.44, and 0.88 10^{-3}/hr.

During the intensive sampling periods of March and May 1974, Eh measurements were made on subsurface drainage water and soils from each tillage treatment (Tables 32-35). Redox potential was measured in both open and submerged drain lines. With the exception of DT drains there was little difference between open and submerged drains. The submerged drains in DT initially had Eh values lower than the open lines, but these difference tended to disappear with time. These differences are likely due to the submerged

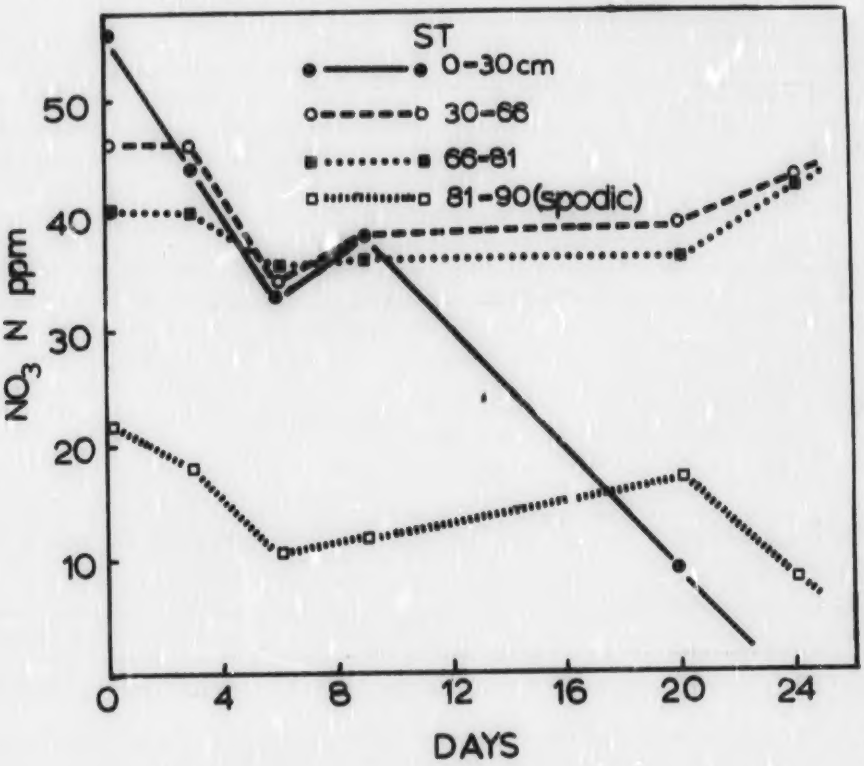


FIGURE 52. Concentrations of NO_3-N in soil-water suspensions prepared with soil samples removed from 0-30, 30-66, 66-81, and 81-90 cm in the ST plot and anaerobically incubated for 24 days. The concentration of the applied NO_3-N solution was 50 µg/ml.

drains keeping the water table higher than the open drains. Why this did not occur in ST and DTL drains is not known.

Redox levels in the soil were measured at 30-cm intervals to 100-cm depth directly over the drain and equidistant between two drains except for ST where measurements were made only over the drain. At 30 and 60 cm the Eh differences between the two locations varied inconsistently. However, at 100 cm the Eh between the drains (except on March 6) was generally lower than at the drain. Differences ranged from 10 to 425 mv and averaged 162 mv. The soil Eh at 100-cm tended to be close to but slightly lower than the drainage water Eh.

Redox potential of the drainage water and soil of the ST treatment remained above the level that would be expected to favor conditions for denitrification during both periods. This is consistent with the laboratory investigation which showed that the surface horizon was the only place where denitrification would occur in the ST treatment. Water was apparently

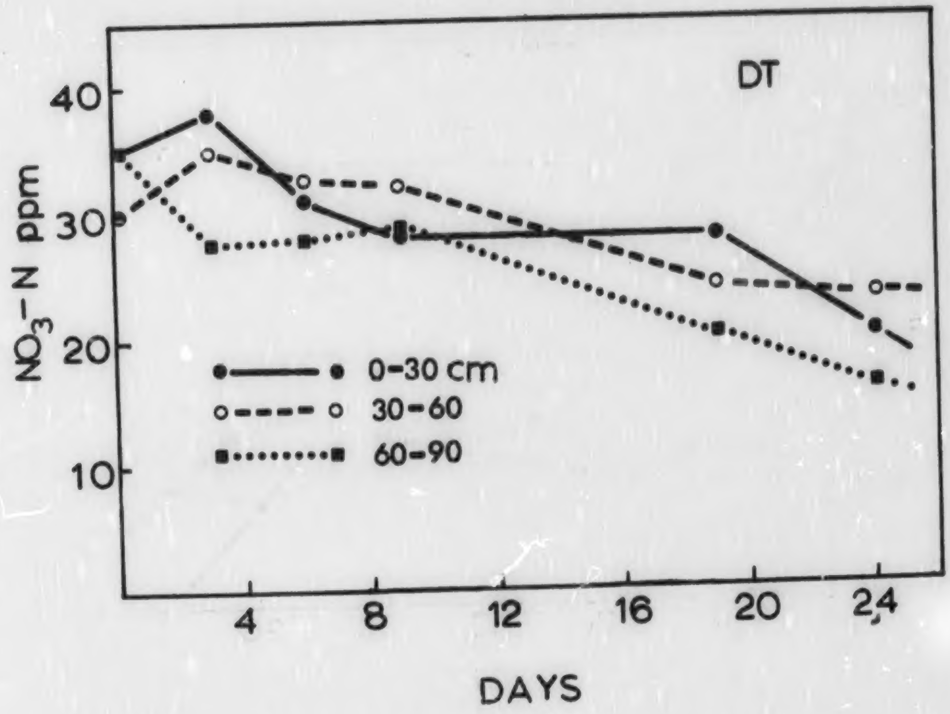


FIGURE 53. Concentrations of NO_3-N in soil-water suspensions prepared with soil samples removed from 0-30, 30-60, and 60-90 cm in DT plot and anaerobically incubated for 24 days. The concentration of the applied NO_3-N solution was 50 μg/ml.

moving through the ST profile fast enough to prevent O_2 depletion and thus the Eh remained high. Only if the water table approached the soil surface would denitrification be expected to occur in the ST surface horizon. Such conditions occurred only during periods of intense rainfall or prolonged irrigation.

In the DT treatment, redox levels at 30 and 60 cm were above the range in which denitrification would be expected. However, at 100 cm depth, values were in the denitrification range. This is especially true for the Eh measured in soil between drains. Drainage water Eh from DT was in the upper part of the denitrification range.

The Eh of the DTL soil at 30-cm was also above the range where denitrification would be expected. At 60-cm Eh was borderline to the denitrification range and at 100-cm it was within this range. Drainage water Eh was again on the borderline of the denitrification range.

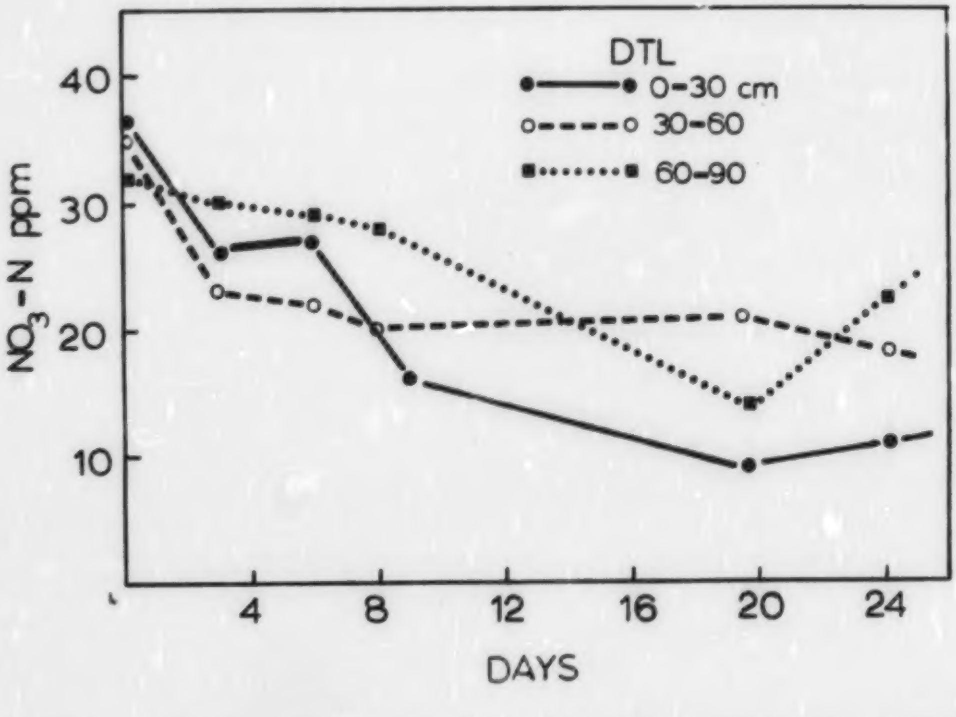


FIGURE 54. Concentrations of NO_3-N in soil-water suspensions prepared with soil samples removed from 0-30, 30-60, and 60-90 cm in the DTL plot and anaerobically incubated for 24 days. The concentration of the applied NO_3-N solution was 50 µg/ml.

Table 31. Redox potentials observed during anaerobic incubation of the DTL soil samples.

Depth	0	3		6		9		19		25	
		avg.	min.	avg.	min.	avg.	min.	avg.	min.	avg.	min.
-cm-	mv										
0-30	515	375	175	420	180	407	-15	380	15	390	145
30-60	525	455	195	365	215	380	20	445	305	400	305
60-90	495	345	235	---	---	405	135	405	135	445	345

SUMMARY

Results from this study indicate that denitrification could provide a significant sink for applied fertilizer nitrogen when rain or irrigation is sufficient to move NO_3-N to within 100-cm depth in the DT and DTL treatments. However, if the added water is sufficient to cause continuous movement of the NO_3-N through the soil and into the subsurface drain, the residence time required for denitrification to occur in any significant amount will depend upon the period of time required for the NO_3-N to move with soil water along a given streamline or pathway from the soil surface to the subsurface drain. NO_3-N from fertilizer applied to the soil directly over a drain should follow the shortest streamlines and thus may have residence times too short for denitrification; whereas NO_3-N from fertilizer applied to the soil furface at a distance midway (9.14 m) between two drains would be expected to follow streamlines with the maximum pathlength and with residence times much greater than that needed for denitrification to occur. Observed drainage responses to irrigation and rainfall suggests that denitrification loss of NO_3-N in fertilized DT and DTL plots should be greater than in the ST plot during subsurface drainage because of the greater rates of denitrification in the subsoil and because of the slower flux of drainage water and thus the longer residence times of NO_3-N within the soil profile. During periods (summer months) of much rainfall and in the absence of subsurface drainage, however,

Table 32. Redox potentials measured in subsurface drainage water during the March, 1974 sampling period.

Treatment	Tile[2]	17	19	21	24	30	40	46	53	64	Avg.
		mv									
ST	0	490	395	420	420	455	485	505	460	460	455
	S	505	445	445	475	490	445	555	520	505	485
DT	0	340	270	290	320	380	350	400	385	400	350
	S	235	215	235	275	330	340	375	380	375	305
DTL	0	725	280	265	305	295	300	290	310	315	345
	S	370	290	285	295	280	300	275	300	310	300

(Column heading over 17–Avg.: Time[1], hrs)

[1] 0 hr = Start of irrigation, March 5, 1976

[2] 0 = Open drain; S = submerged drain

denitrification losses could easily occur more rapidly in the surface ST soil than in the surface DT and DTL soils since the residence times required for denitrification (with imposed conditions of no net soil water flow) were 2.55 and 5.10 times greater in surface DTL and DT soil than in surface ST soil.

Table 33. In situ redox potentials of ST, DT and DTL soils during the March, 1974 sampling period.

Electrode depth	March 5		March 6		March 7		March 8	
	A*	B*	A	B	A	B	A	B
inches								
				ST				
12	660	---	495	---	475	---	455	---
24	630	---	575	---	505	---	535	---
36	435	---	465	---	465	---	545	---
				DT				
12	790	475	605	465	540	555	625	515
24	750	470	555	540	455	535	540	465
36	365	305	295	325	295	230	415	185
				DTL				
12	545	590	345	455	445	505	345	400
24	750	550	355	485	335	505	330	310
36	695	410	225	335	325	190	335	105

*A = electrodes placed over the drain.
B = electrodes placed between two drains.

Table 34. Redox potentials measured in subsurface drainage water from ST, DT and DTL plots during the May, 1974 sampling period.

		Time[1], hrs									
Treatment	Tile	-8	6	16	21	26	39	45	63	66	avg.
		mv									
ST	0[2]	415	430	435	500	458	455	480	453	520	460
	S[3]	445	455	475	505	505	515	495	490	520	490
DT	0	395	390	380	390	375	425	435	410	425	400
	S	340	340	305	340	375	410	385	350	380	358
DTL	0	330	325	305	365	410	355	395	340	370	355
	S	290	320	250	350	425	410	395	310	395	350

[1] 0 hr = start of irrigation, May 21, 1976

[2] Open drains

[3] Submerged drains

Table 35. In situ redox potentials of ST, DT and DTL soils during the May, 1974 sampling period.

Electrode depth	May 20		May 22		May 23		May 24	
	A*	B*	A	B	A	B	A	B
inches								
				ST				
12	555	---	400	---	430	---	460	---
24	365	---	335	---	335	---	335	---
36	580	---	495	---	505	---	520	---
				DT				
12	635	710	530	615	485	600	420	565
24	505	460	350	505	345	555	275	420
36	280	-20	330	-25	370	-55	335	220
				DTL				
12	460	690	350	565	355	530	365	515
24	505	430	235	415	255	345	255	305
36	280	255	305	265	255	245	265	190

*A = electrodes placed over drain.
B = electrodes placed between two drains.

SECTION VII

DISTRIBUTION OF NO_3-N CONCENTRATION AND WATER PRESSURE IN A DEEP-TILLED SPODOSOL

EXPERIMENTAL METHODS AND PROCEDURES

The simultaneous transport of water and nutrients in subsurface-drained Spodosols is particularly important to phenomena such as nutrient uptake by plant roots, leaching loss of nutrients into nearby canals, and the overall consideration of the use-efficiency of applied fertilizer. During June of 1975 spatial (2-dimensions) distributions of soil water pressure and concentration of NO_3-N were measured in DTL soil surrounding a subsurface drain. These distributions were determined for selected times following a sequence of fertilizer and irrigation water applications and were used to analyze water and NO_3-N movement in the soil.

Soil water tensiometers comprised of porous ceramic cups, each hydraulically connected to a separate mercury manometer, and soil solution samplers comprised of slightly larger porous ceramic cups connected to a plastic pipe were installed in the soil at selected horizontal and vertical distances from a subsurface drain. Tensiometer cups were placed at vertical depths of 15, 30, 60, and 100 cm in the soil directly over the drain and at 0.91, 4.57 and 9.14 m distances on both sides of the drain. The solution sampler cups were placed at similar locations in the soil but were placed approximately 30 cm from the tensiometer cups. All tensiometers and solution samplers were located within a row of citrus trees which was perpendicular to the drain. Soil water pressure was determined from readings of tensiometers, and soil solution samples were removed from the soil solution samplers. A small electrical vacuum pump was used to establish a partial vacuum within the air-space of the sampler. Six hours later the vacuum was released and a sample of the extracted water within the sampler was removed. These samples were later analyzed for NO_3-N concentration.

Soil water pressure and NO_3-N concentration data was used to determine 2-dimensional graphs of water pressure and NO_3-N contours in the soil effected by the subsurface drain. On the morning of June 10, 1975 a quarterly application of 530 kg/ha of an 8-2-8 fertilizer was made. This application contained 42.42 kg/ha of N (19.07 kg/ha of NO_3-N and 23.31 kg/ha of NH_4-N). Between the period of 3:30 PM on June 10 and 1:00 AM on June 11, 3.86 cm of irrigation water was applied to the plot. On June 12, 0.41 cm of rain occurred.

RESULTS AND DISCUSSION

Soil water pressure distributions are given in Figs. 55-62 for 3:00 PM on June 10, 9:50 PM on June 10, 1:10 AM on June 11, 2:15 PM on June 11, 4:00

PM on June 12, 7:45 AM on June 13, June 16, and June 18. These distributions show that a water table (h=0) occurred in the soil between 65 to 75 cm depth even prior to initiation of the irrigation. Soil above those depths were water unsaturated. Contours of equal soil water pressure can be converted to contours of soil water content using the characteristic water data from Hammond, Carlisle, and Rogers (1971). Prior to initiation of irrigation the DTL soil was slowly undergoing drainage as indicated by the larger vertical gradients for soil water directly above the drain. However, the water table was relatively flat at horizontal distances greater than 1.5 m from the drain.

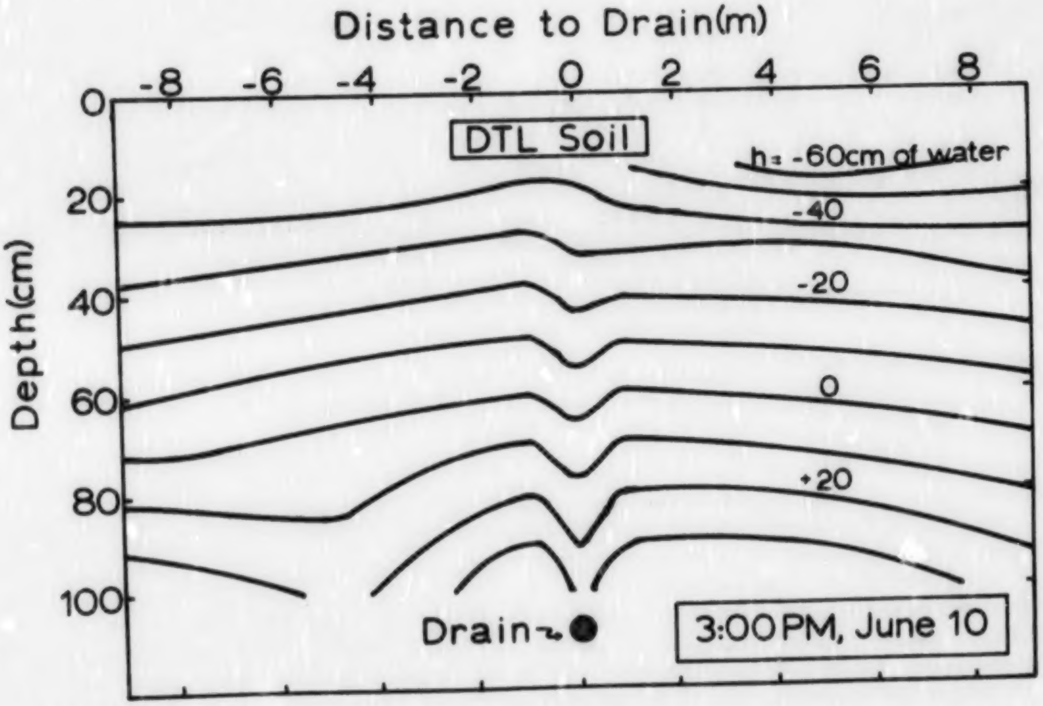


FIGURE 55. Spatial distribution of soil water pressure (h) in DTL soil surrounding a subsurface drain at 3:00 PM on June 10, 1975. Lines of equal water pressure are shown.

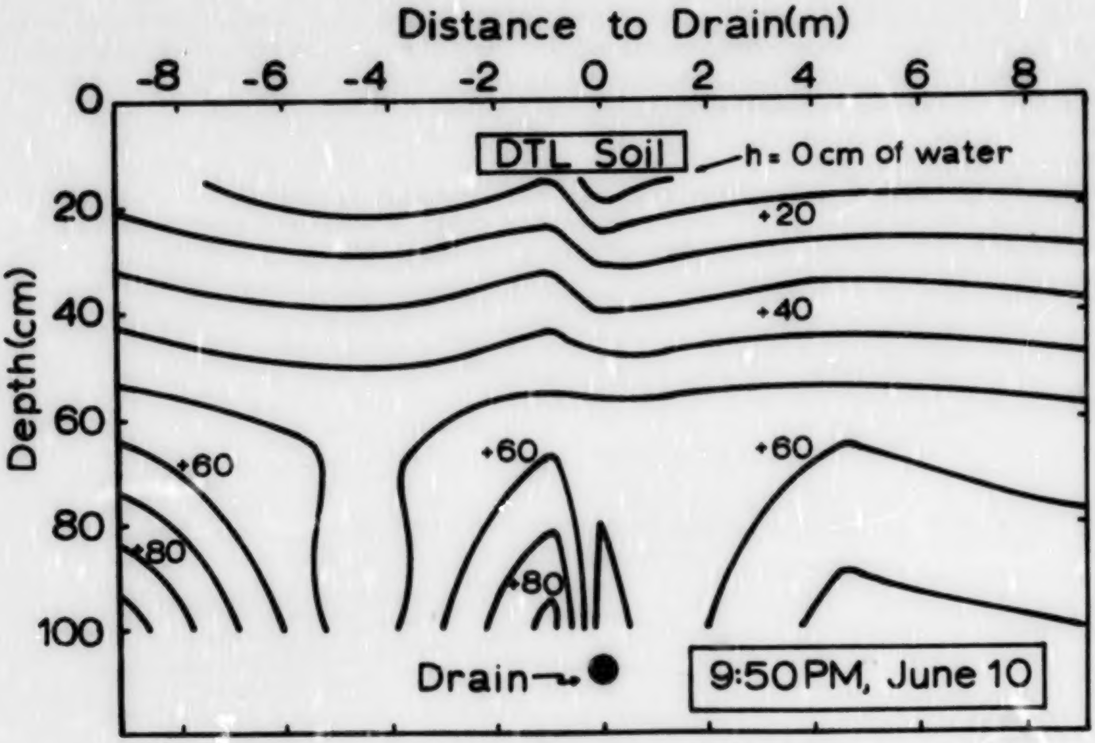


FIGURE 56. Spatial distribution of soil water pressure (h) in DTL soil surrounding a subsurface drain at 9:50 PM on June 10, 1975.

Six hours after initiation of the irrigation at 3:30 PM, the water table (h=0) had risen to the top 15 cm of the soil profile and ten minutes after terminating the irrigation at 1:00 AM on June 11 the entire soil profile was water-saturated. During the first 13.25 hours of the post-infiltration period the soil underwent sufficient drainage to lower the water table to a depth of 25 to 30 cm from the surface by 2:15 PM on June 11. By 4:00 PM on June 12, which was 39 hours after cessation of irrigation, the water table was still located at a depth of 35-40 cm, indicating a very slow drainage rate for this deep-tilled sandy soil. The relatively larger gradients of hydraulic head in the soil near the drain compared to those away from the drain suggests the presence of a localized resistance to water flow in the immediate vicinity of the drain (Roger, Simmons and Hammond, 1971). Drainage is also relatively slow in this deep-tilled soil because of the relatively small values of hydraulic conductivity (Hammond, Carlisle, and Rogers, 1971) at water-saturation.

By 7:45 AM on June 13, or 2.25 days after cessation of irrigation, the water table was located at 40-45 cm depth, and by 5.5 days (June 16) after cessation of irrigation the water table was located at 55-65 cm depth. By June 18 or 7.5 days after cessation of irrigation the water table had returned to the pre-irrigation depth of 65-75 cm. Even after 7.5 days the soil was still undergoing a slow rate of drainage and water contents in the soil (Hammond, Carlisle and Rogers, 1971) ranged from saturation (34.0% by volume) to approximately 27% by volume at 15 cm depth. Thus this soil water pressure data clearly illustrate the relatively slow drainage of the DTL soil and the corresponding high soil water contents in this deep-tilled soil. The slow decrease of the water content in the surface 60 cm of this sandy soil is largely responsible for better growth of citrus trees on DT and DTL plots relative to the ST plot which drains very rapidly to give a corresponding rapid decrease of soil water content. The slow drainage of the DTL soil should also result in slower velocities of soil water movement which in turn should provide slower rates of NO_3-N leaching in the soil.

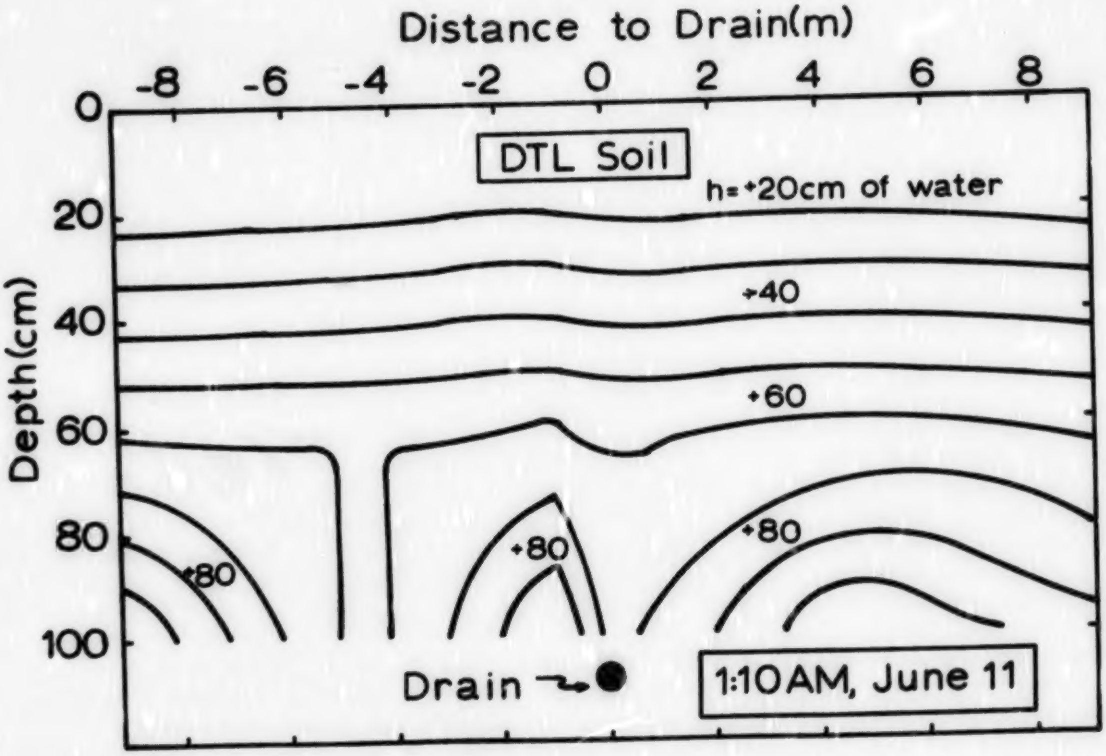


FIGURE 57. Spatial distribution of soil water pressure (h) in DTL soil surrounding a subsurface drain at 1:10 AM on June 11, 1975.

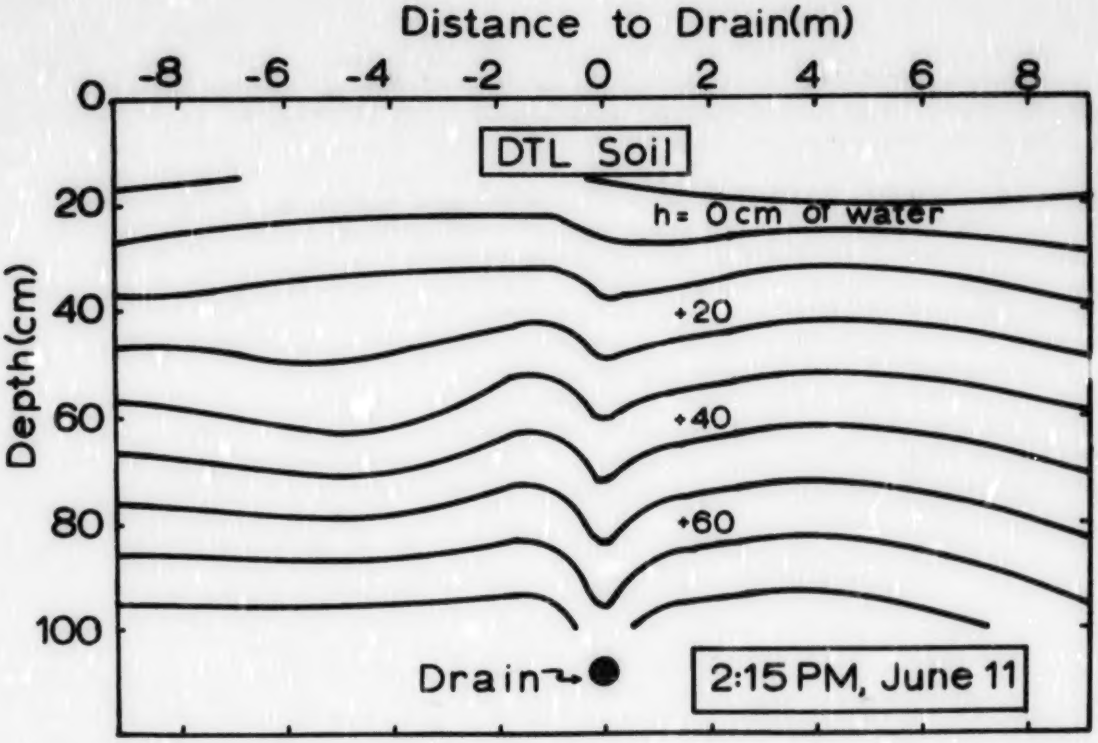


FIGURE 58. Spatial distribution of soil water pressure (h) in DTL soil surrounding a subsurface drain at 2:15 PM on June 11, 1975.

Distributions of NO_3-N concentrations in the DTL soil are presented in Figs. 63-67 for noon on June 10, midnight on June 10, 9:30 AM on June 11, 2:00 PM on June 11, and 10:00 PM on June 12. Prior to initiation of irrigation (3:30 PM on June 10) NO_3-N concentrations were relatively high in the top 60 cm soil located at horizontal distances greater than 2 m from the drain. THese concentrations were as high as 22 μg/ml as compared to concentrations generally less than or equal to 2 μg/ml in soil beneath 60 cm depth and in all of the soil directly above the drain. Initial concentrations of nitrate in the soil probably originated either as NH_4-N or NO_3-N from previous quarterly applications of fertilizer (the last application was 3 months prior to this time). Since the water table at this time was approximately at the 65-70 cm depth, the observed distributions of NO_3-N may be attributed to loss of nitrogen by denitrification in the water-saturated lower portion of the soil profile and gain of NO_3-N by nitrification of NH_4-N previously adsorbed to soil particles in the water-unsaturated (and aerobic) upper 60 cm of the soil profile. The low concentrations of NO_3-N in soil above the drain coincides with the soil which usually has the largest gradients of hydraulic head and thus the largest velocities for soil water flow for periods of drainage following rainfall or irrigation events. Thus the relatively rapid soil water movement in the soil above the drain during previous rainfall events probably resulted in greater leaching of applied nitrogen and thus the lower observed concentrations of NO_3-N.

By midnight on June 10 or exactly 8.5 hours after initiation of irrigation at 3:30 PM, the contour for 10 µg/ml of NO_3-N in the soil solution had moved downward from the pre-irrigation location of 40-50 cm on either side of the drain to the 50-70 cm depth. Concentrations greater than 100 µg/ml were located at approximately 30 cm depth at 9.14 m to the left of the drain and at 15 cm depth between 3-7 m to the right of the drain. NO_3-N concentrations in the vicinity of the drain were considerably less than 10 µg/ml, however. Although the NO_3-N distribution clearly indicates the influence of the

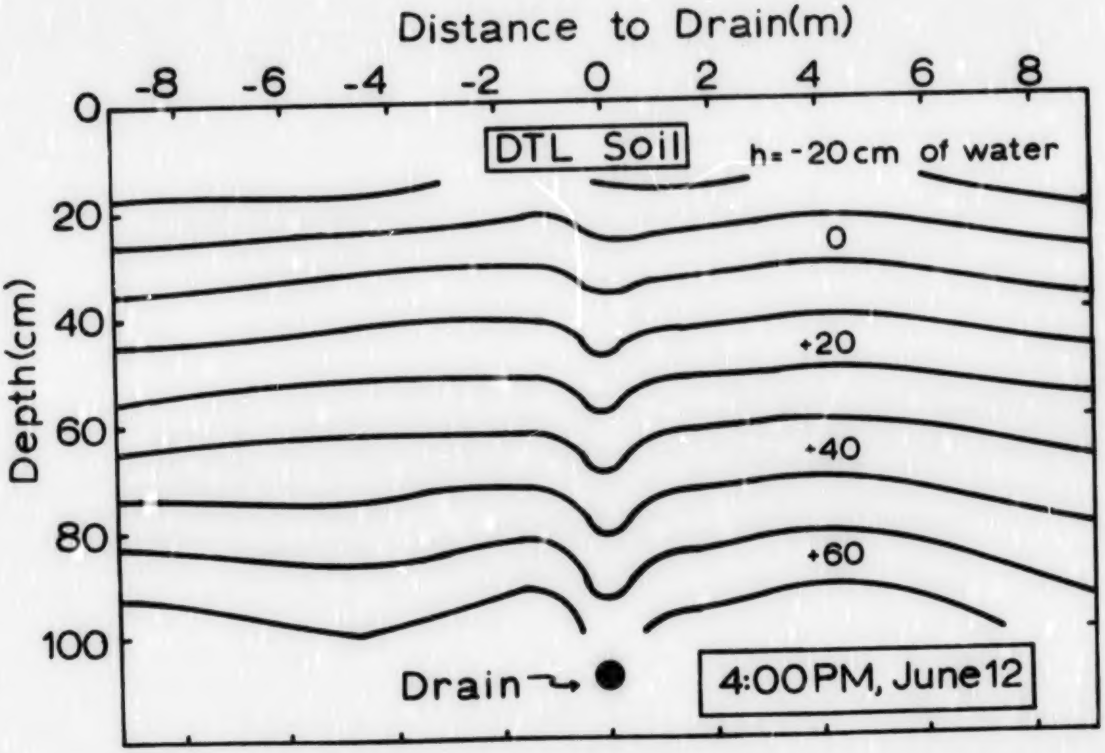


FIGURE 59. Spatial distribution of soil water pressure (h) in DTL soil surrounding a subsurface drain at 4:00 PM on June 21, 1975.

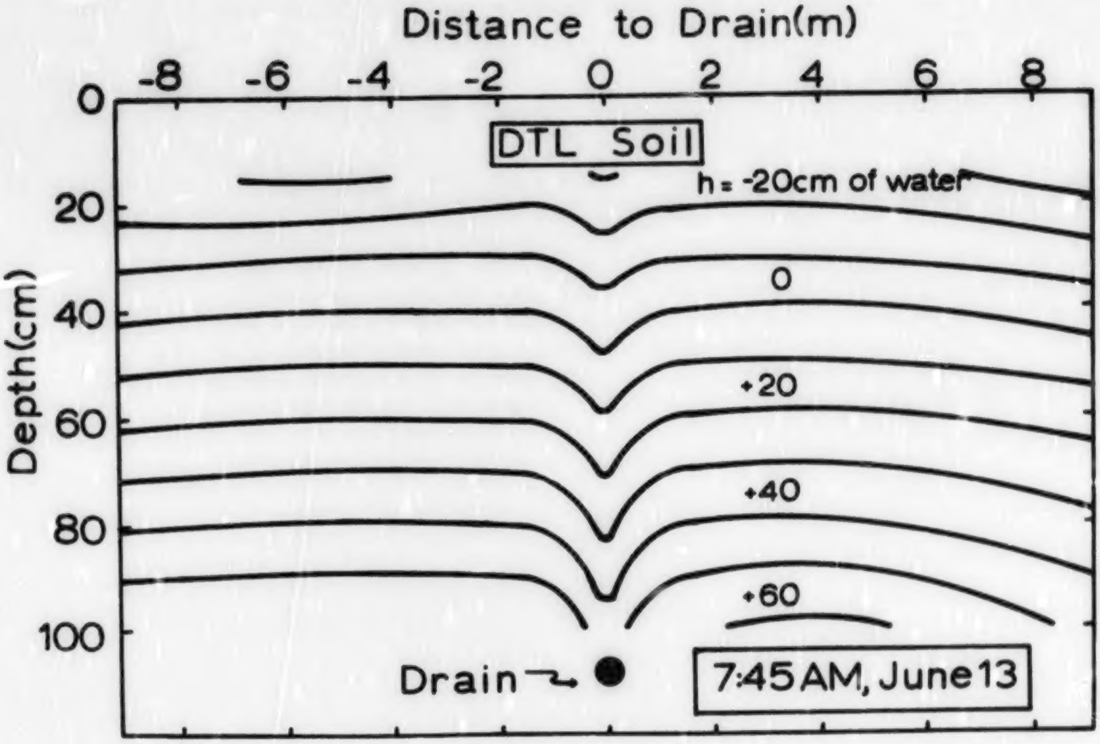


FIGURE 60. Spatial distribution of soil water pressure (h) in DTL soil surrounding a subsurface drain at 7:45 AM on June 13, 1975.

infiltrating water moving the applied NO_3-N downward into the soil, the right-hand side distribution clearly was not a mirror image of the left-hand side as were the soil water pressure distributions.

By 9:30 AM on June 11 or 8.5 hours after cessation of irrigation, the NO_3-N concentration distribution indicates a gradual downward movement of the NO_3-N. By 13 hours (2:00 PM on June 11) after cessation of irrigation, the concentration distributions show that the 10 μg/ml contours had progressed to the 80-85 cm depth on both sides of the drain but was located at the 30-35 cm depth in soil directly above the drain. Concentrations of NO_3-N in the soil solution near the drain was still much less than 10 μg/ml. Approximately 3 days (10:00 PM on June 12) after cessation of irrigation, the distribution of NO_3-N was essentially the same as that on June 11 at 2:00 PM. Thus these NO_3-N distributions suggest that concentrations of NO_3-N in subsurface drainage water from DTL were low (<< 10 μg/ml) compared to maximum concentrations observed in the top 60 cm of surface soil greater than 2 m distance from the drain.

Water flux and concentrations of NO_3-N in water from the submerged drain for the DTL plot are presented in Fig. 68 for the period June 10-24, 1975. The water flux increased to a maximum value at 4:00 PM on June 11 and then slowly decreased with time thereafter. Concentration of NO_3-N in the subsurface drainage was initially 0.37 µg/ml on June 10 and increased to a maximum value of 7.02 µg/ml on June 16 at 8:00 PM. A comparison between Fig. 68 and Figs. 63-67 indicates that changes in concentration of NO_3-N in subsurface drainage followed changes in concentration in the soil solution immediately surrounding the drain tube.

SUMMARY

Spatial distributions of soil water pressure and NO_3-N concentration in DTL soil were determined for a period of days following a sequence of fertilizer and irrigation-water applications. Relatively slow drainage occurred after the 3.86 cm of irrigation and water flow from the drain tube had not ceased even after 7.5 days following cessation of water application. The

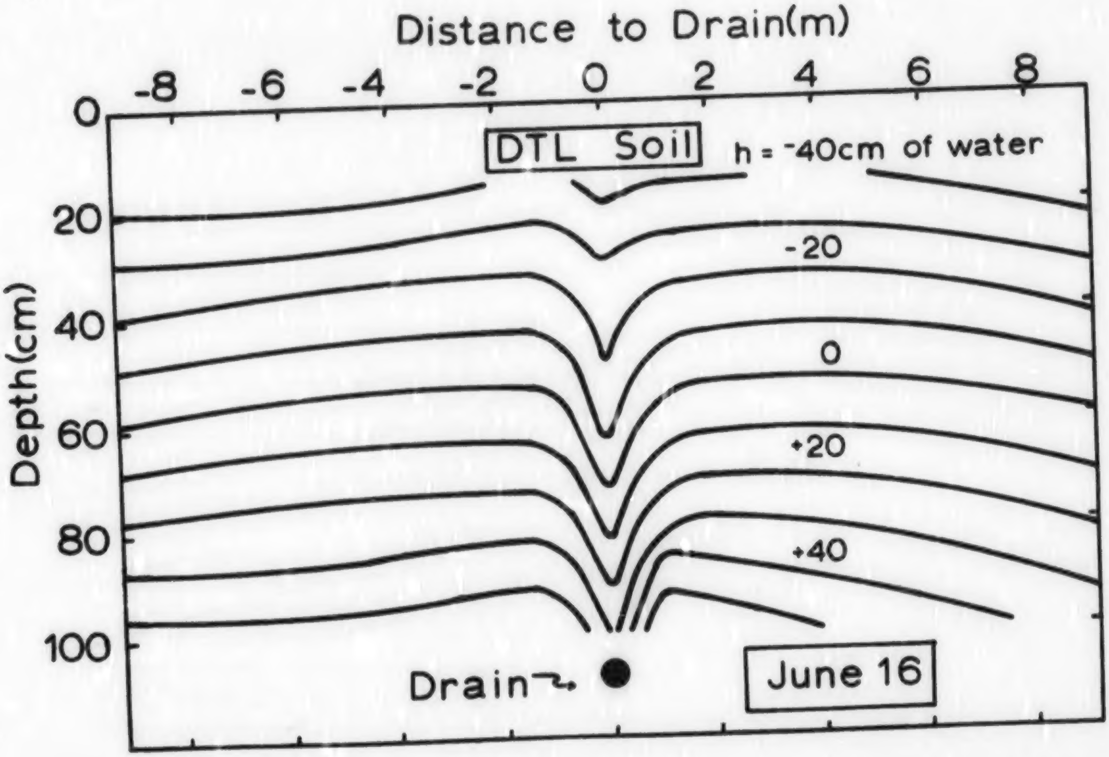


FIGURE 61. Spatial distribution of soil water pressure (h) in DTL soil surrounding a subsurface drain on June 16, 1975.

slow drainage provided three beneficial effects: (1) water contents in the top 60 cm of soil remained relatively high even after 7.5 days, thus providing an optimum soil water environment for growth of citrus trees, (2) slow drainage resulted in relatively slow changes in soil water content and thus low flow velocities for leaching of NO_3-N, and (3) during the entire 7.5 day period a water table was located at some depth in the soil, providing an aerated zone of soil for nitrification of applied NH_4-N above the water table and a denitrification sink for NO_3-N in the lower portion of the soil near the subsurface drain.

Although NO_3-N concentrations in soil solution samples extracted from the upper portion of the soil drainage field were as high as 120 µg/ml, concentrations of NO_3-N in the subsurface drainage water were always less than 8 µg/ml.

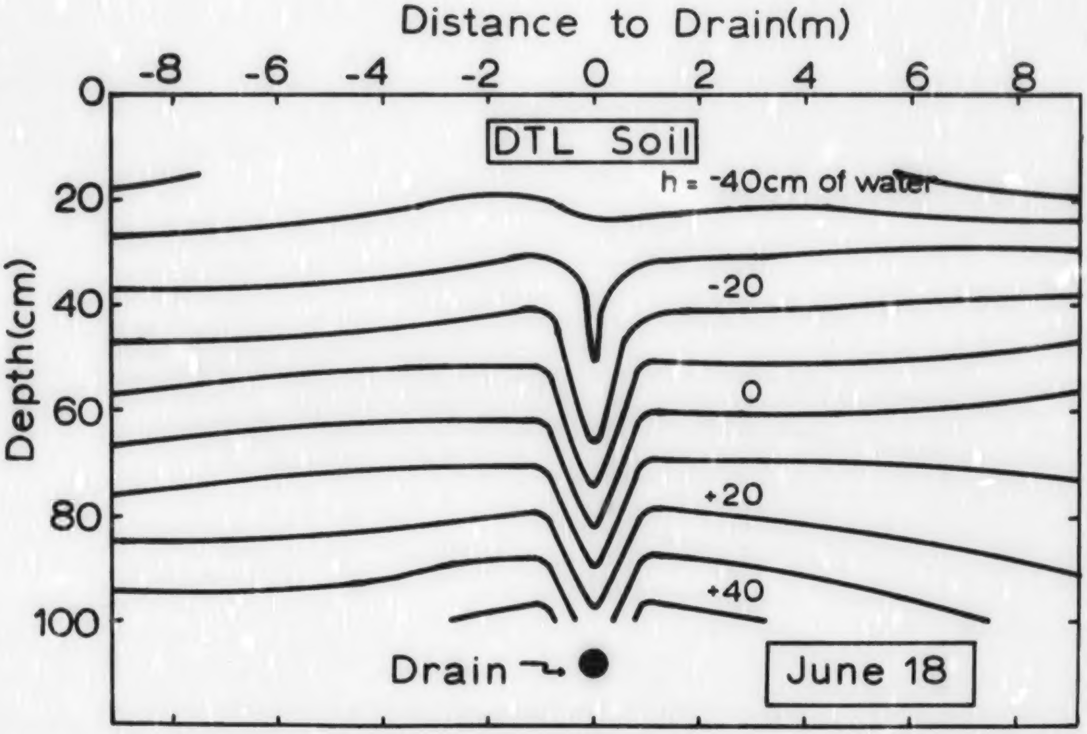


FIGURE 62. Spatial distribution of soil water pressure (h) in DTL soil surrounding a subsurface drain on June 18, 1975.

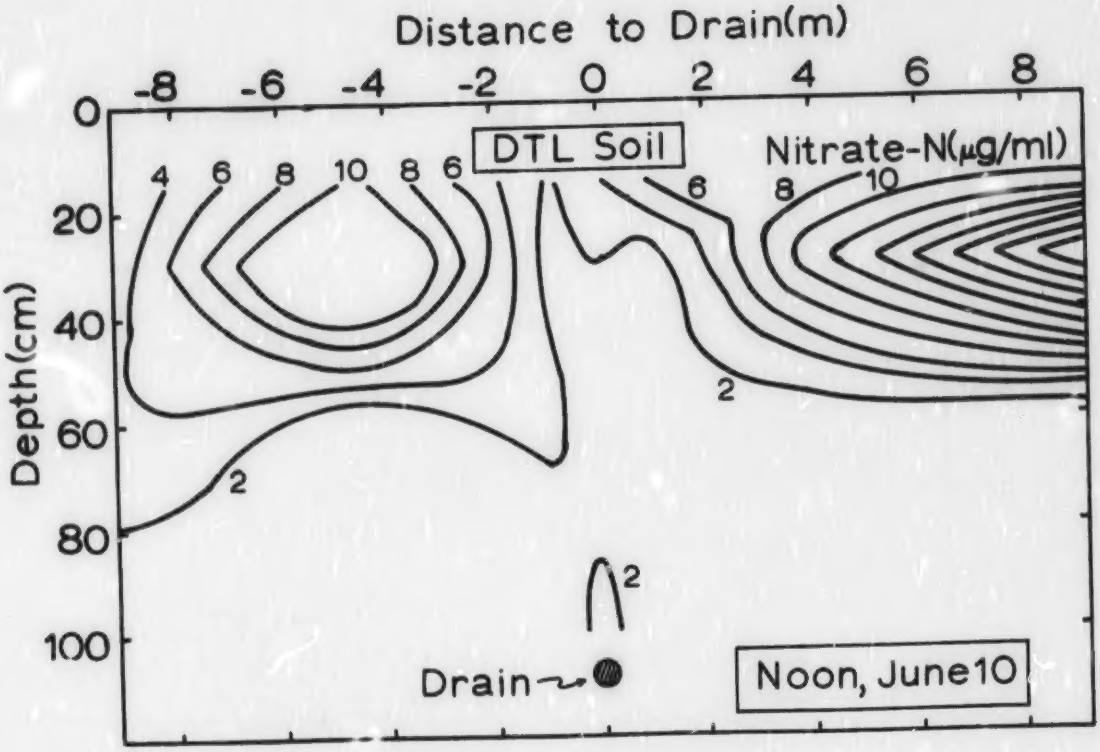


FIGURE 63. Spatial distribution of NO_3-N concentration in the solution of DTL soil surrounding a subsurface drain at noon on June 10, 1975. Lines of equal concentration are shown.

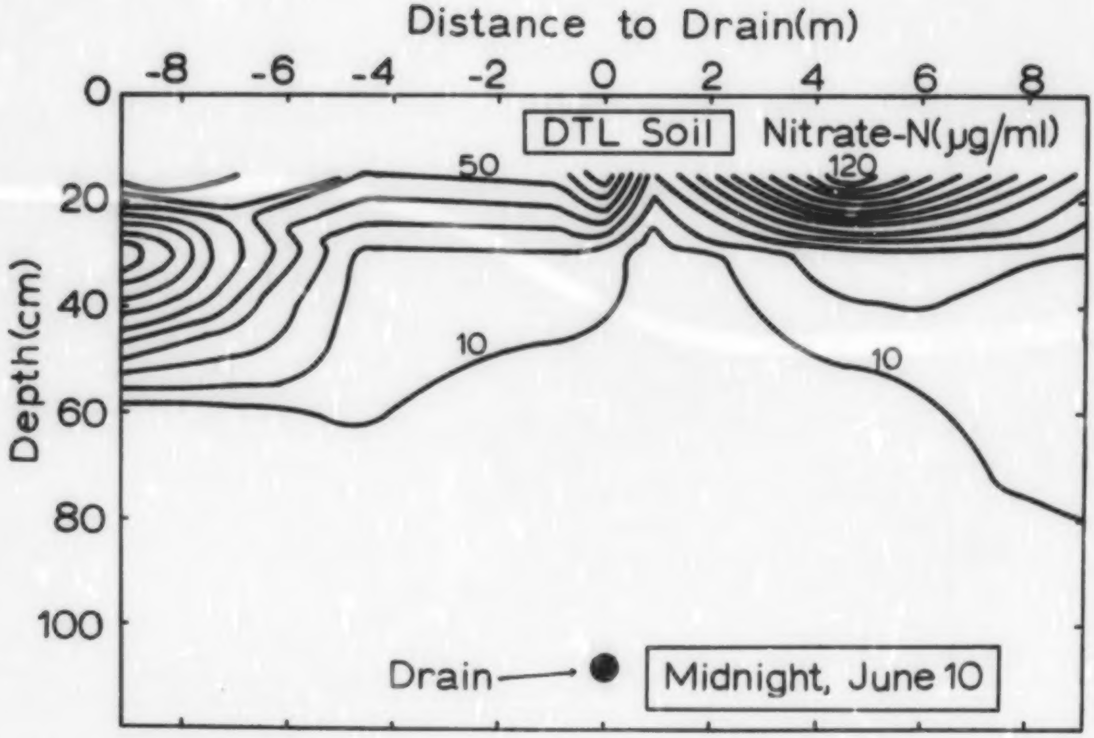


FIGURE 64. Spatial distribution of NO_3-N concentrations in the solution of DTL soil surrounding a subsurface drain at midnight on June 10, 1975.

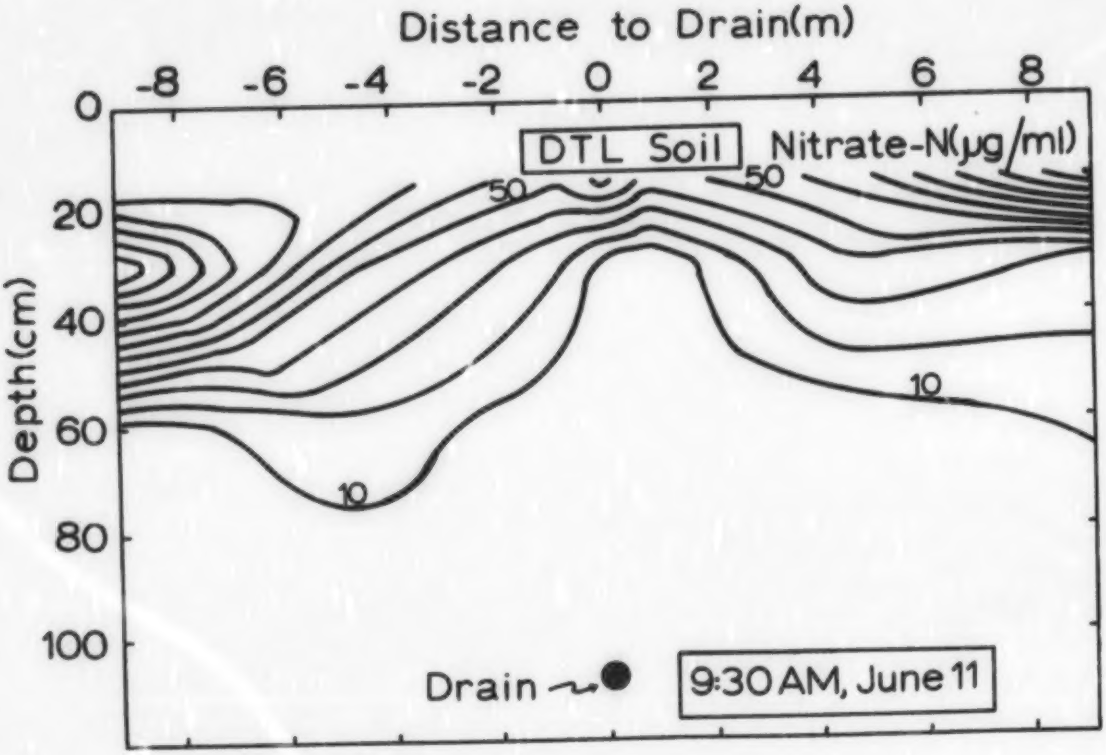


FIGURE 65. Spatial distribution of NO_3-N concentrations in the solution of DTL soil surrounding a subsurface drain at 9:30 AM on June 11, 1975.

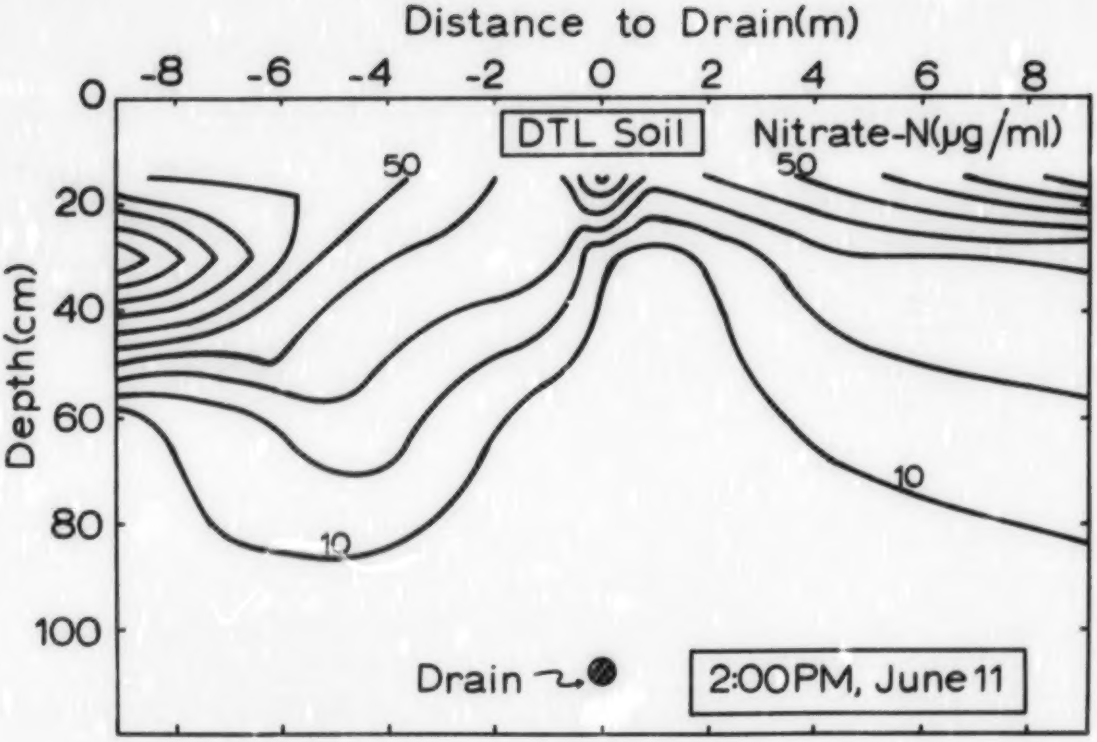


FIGURE 66. Spatial distribution of NO_3-N concentration in the solution of DTL soil surrounding a subsurface drain at 2:00 PM on June 11, 1975.

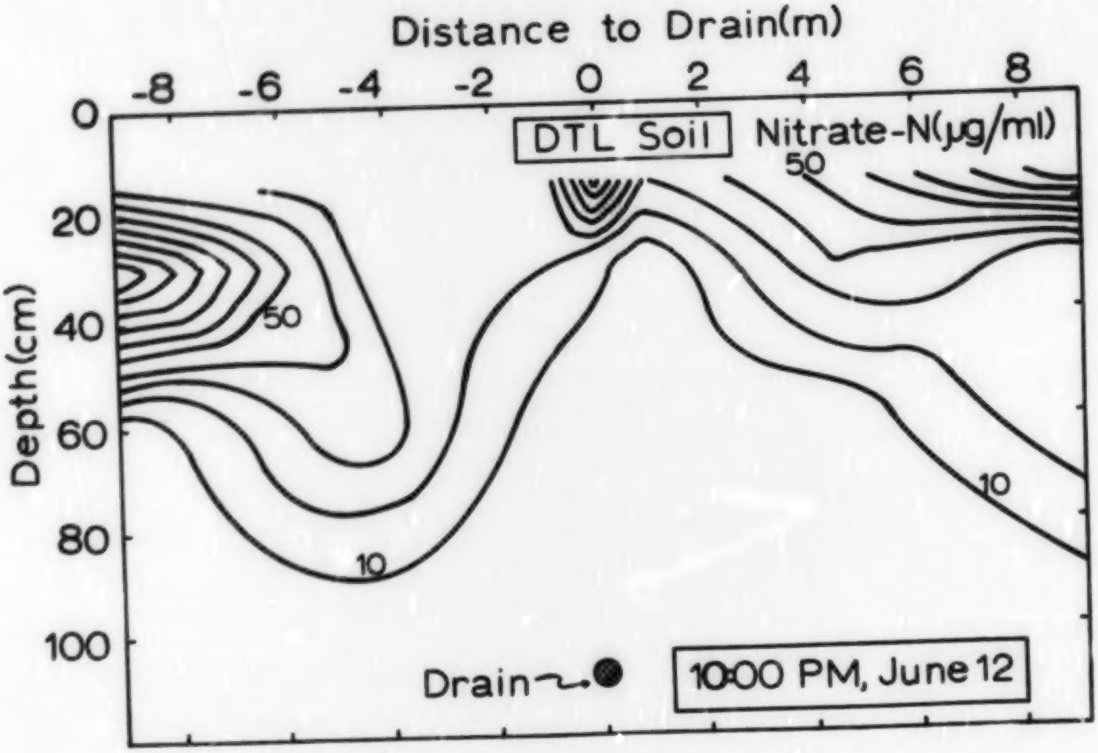


FIGURE 67. Spatial distribution of NO_3-N concentration in the solution of DTL soil surrounding a subsurface drain at 10:00 PM on June 12, 1975.

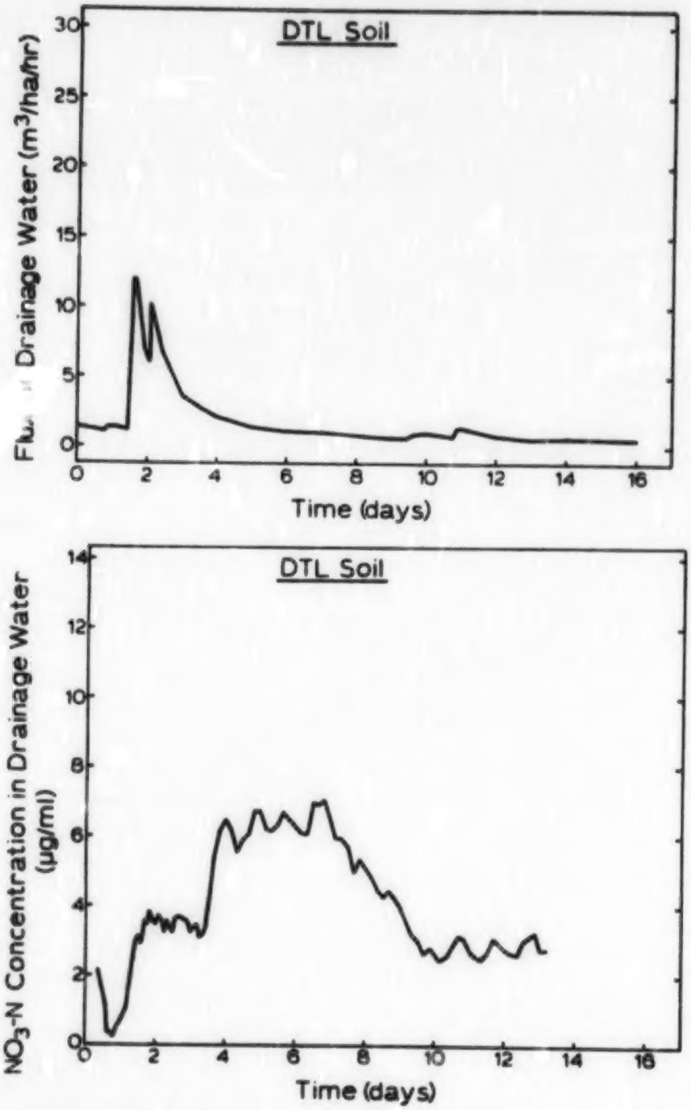


FIGURE 68. Flux of subsurface drainage and NO_3-N concentration in the drainage water from the DTL plot with time during the 14-day period from June 10-24, 1975.

SECTION VIII

PHOSPHORUS ADSORPTION-DESORPTION AND TRANSPORT IN SOIL COLUMNS

LABORATORY EXPERIMENTS

Selim et al. (1975) and Mansell et al. (1976) examined the dynamics of processes which remove phosphorus from the soil solution during miscible displacement of a phosphate solution through undisturbed cores of Oldsmar sand (Spodosol). These cores were removed from an unfertilized and untilled area adjacent to the SWAP citrus grove near Fort Pierce. Experimental methods and procedures are recorded elsewhere (Selim et al., 1975 and Mansell et al., 1976).

Adsorption isotherms plotted as phosphorus sorbed, S, (µg/g of soil) versus phosphorus concentration, C, (µg/ml) in solution were linear for the A_2 subsoil and highly nonlinear for the surface A_1 and subsurface B_{2h} or Spodic horizons. The isotherms extended over a C range from 0-100 µg/ml for A_1 and A_2 horizon materials and from 0-800 µg/ml for the B_{2h} horizon.

Phosphorus breakthrough curves (relative concentration, C/C_o, versus relative volume of effluent, V/V_o) were examined for miscible displacement of aqueous solutions of P and Cl anions from undisturbed cores of A_1, A_2, and B_{2h} soil materials. The relatively inert Cl anion was observed to move more rapidly than the more chemically active P anion through all three soil materials. Although sorption processes resulted in some retardation of the P breakthrough curves for the A_2 soil, the curve shape was very similar to that for the Cl. Breakthrough curves for P in effluent from A_1 and B_{2h} soils were assymetrical and extensive tailing was observed for the desorption phase of the miscible displacement.

Mansell et al (1976) used a transport equation for transport of reactive solutes through soil to simulate P breakthrough curves for the A_2 (Fig. 69) and A_1 (Fig. 70) soil cores. Reversible instantaneous as well as kinetic adsorption-desorption processes gave relatively good descriptions of P transport through these soils.

A MATH MODEL FOR TRANSPORT AND TRANSFORMATION OF PHOSPHORUS IN SOIL

With increasing residence time in the soil, orthophosphate-P applied to the soil undergoes a progressive decrease in water-solubility and availability to plants growing in the soil. Since several simultaneous chemical and physical reactions are known to transform applied P to several less-soluble forms, Mansell et al. (1976) developed a mechanistic, multistep kinetic model to describe both the transformations and transport of applied P during water flow through soil.

Phosphorus transformations were governed by reaction kinetics and convective-dispersion theory was used to describe P transport in soil. Six kinetic reactions - adsorption, desorption, mobilization, immobilization, precipitation, and dissolution - were considered to control P transformations between soluble, adsorbed, immobilized (chemisorbed), and precipitated phases. A schematic diagram of the P transformations is presented in Fig. 71.

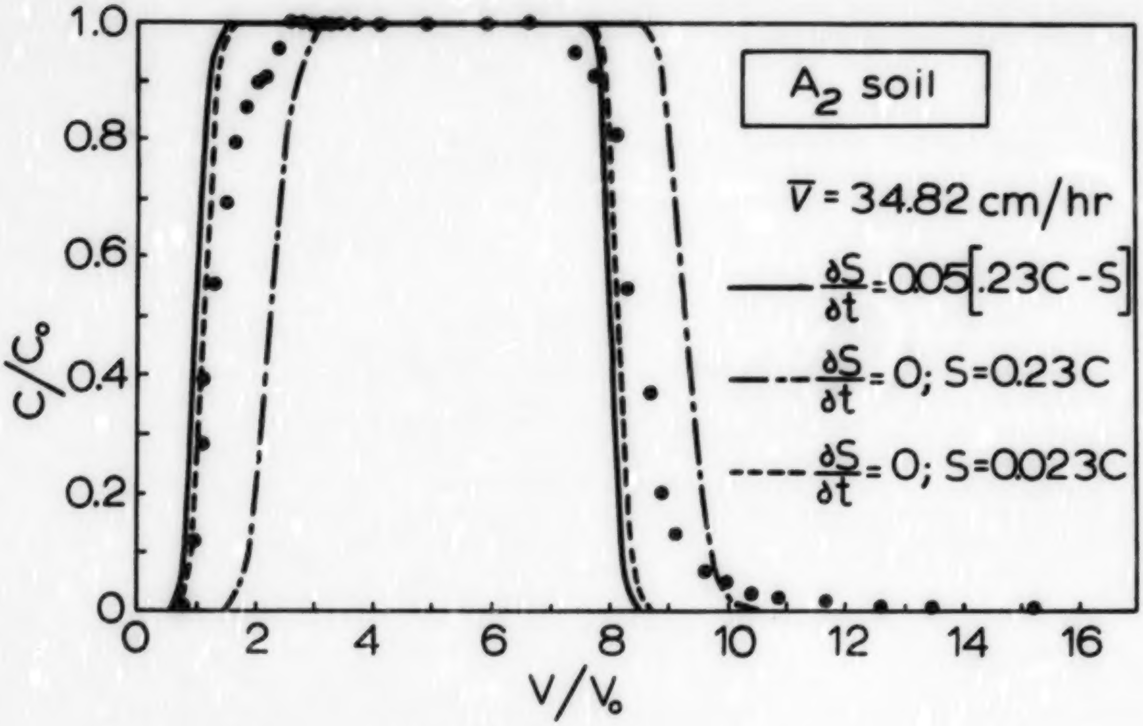


FIGURE 69. Experimental data and predicted breakthrough curves (Mansell et al. 1977) for phosphorus concentrations in aqueous effluent eluted from a water-unsaturated core of subsurface (A_2) Oldsmar sand.

The model was used to simulate P movement in a 100 cm long soil column to which a 100 μg/ml solution of soluble P was applied for a period of 2 hours at a steady water flux of 2.857 cm/hr. Water was then applied for the next 98 hours at the same steady flux. Distributions of P in solution and sorbed phases for a selected standard combination of values for the kinetic rate coefficients is shown in Fig. 72. The striking feature of the solution phase P is the very rapid attenuation of concentration with time and depth. After the first 2 days (approximately 50 hrs.), the maximum concentration of P in solution was only 1 μg/ml and no appreciable P in either solution or sorbed phases occurred beneath the 36 cm depth. The time-dependency of the kinetic reactions provided a very distinct time lag between solution and sorbed phases of P. In Fig. 73 the total quantity of solution phase P in the soil was observed to decrease very rapdily with time as the adsorbed, precipitated and immobilized phases increased. Thus the kinetic transformations for P applied to this soil tends to decrease the downward movement and thus the leaching loss of P from the column. Laboratory and field experiments will be needed in the future to validate and verify the assumptions used in this model.

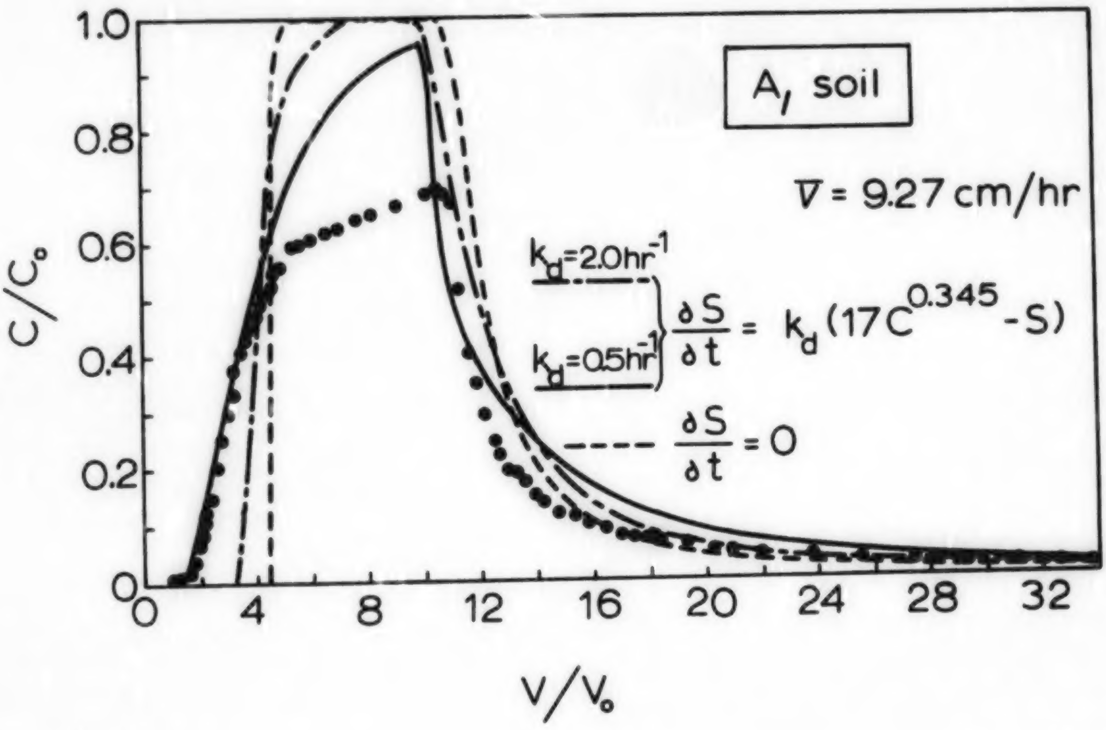


FIGURE 70. Experimental data and predicted breakthrough curves (Mansell et. al. 1977) for phosphorus concentrations in aqueous effluent eluted from a water-unsaturated core of subsurface (A_1) Oldsmar sand.

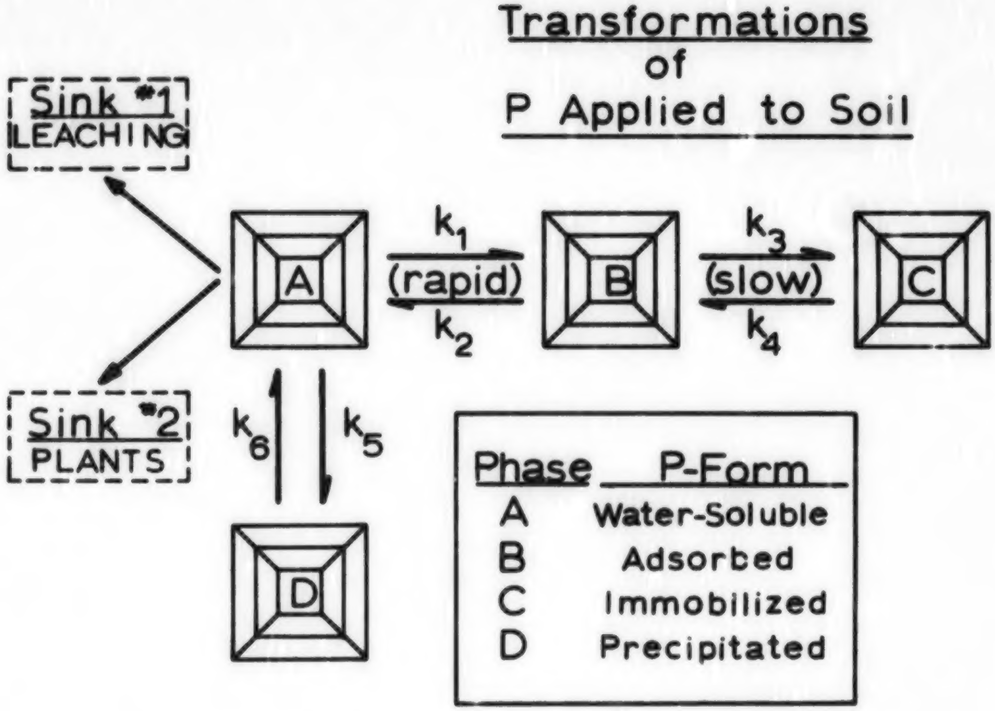

Transformations
of
P Applied to Soil
Sink #1
LEACHING
Sink #2
PLANTS
A
B
C
D
k_1
(rapid)
k_2
k_3
(slow)
k_4
k_5
k_6
Phase P-Form
A Water-Soluble
B Adsorbed
C Immobilized
D Precipitated

FIGURE 71. A schematic diagram of a mechanistic multistep mathematical model (Mansell, Selim and Fiskell, 1977) for transformations of P applied to soil.

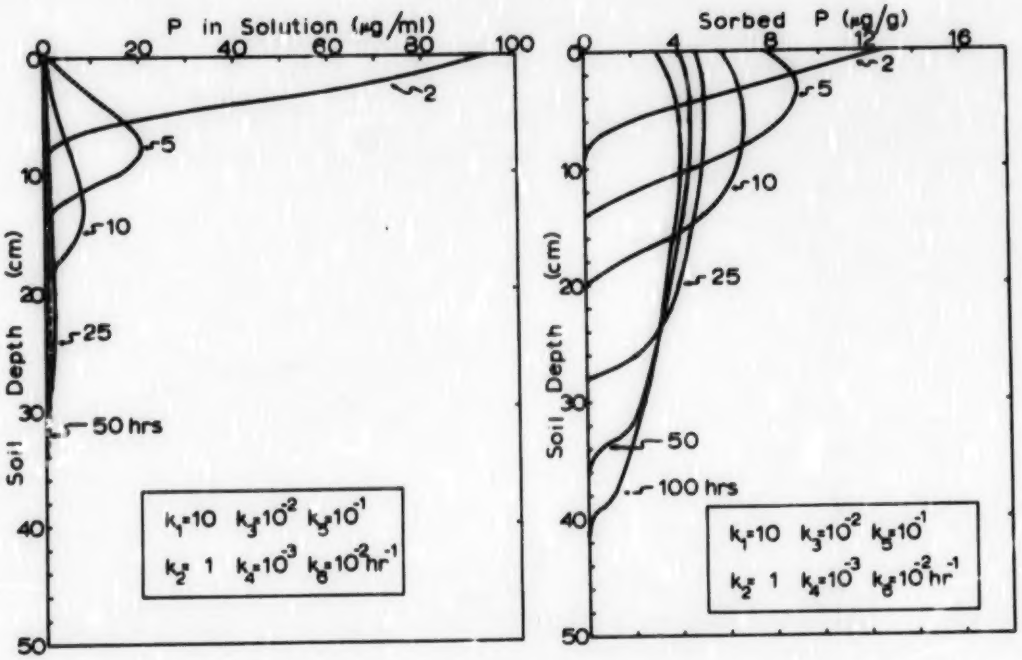


FIGURE 72. Distributions of solution and sorbed phases of applied P during miscible displacement through a 100 cm long column of a theoretical soil using a mechanistic, multistep kinetic model (Mansell, Selim, and Fiskell, 1977).

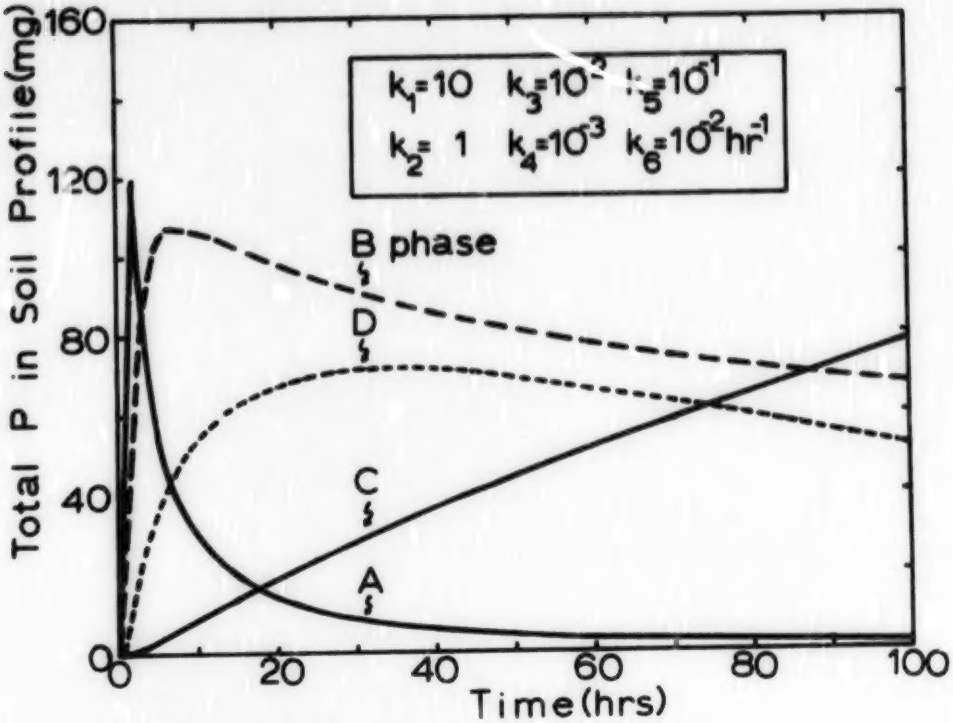


FIGURE 73. Total quantities of soluble, adsorbed, immobilized, and precipitated phase P in a 100 cm column of theoretical soil with time during miscible displacement as predicted by the model of Mansell, Selim, and Fiskell, (1977).

REFERENCES

1. Alberts, R.R., E.H. Stewart, and J.S. Rogers. 1971. Ground water recession in modified profiles of Florida flatwood soils. Soil and Crop Sci. Soc. of Florida Proc. 31:216-217.

2. Ayers, R.S. and R.L. Branson, Editors. 1973. Nitrates in the Upper Santa Ana River Basin in relation to groundwater pollution. Bulletin No. 861, California Agricultural Experiment Station, Division of Agricultural Sciences, University of California.

3. Biggar, J.W. 1970. Pesticide movement in soil water. Pages 107-119 in Pesticides in The Soil: Ecology, Degradation, and Movement, Michigan State University, East Lansing, Michigan.

4. Biggar, J.W. and R.B. Corey. 1969. Agricultural drainage and eutrophication. Pages 404-445 in Eutrophication: Causes, Consequences, Correctives, National Academy of Sciences, Washington, D.C.

5. Bingham, F.F., S. Davis, and E. Shade. 1971. Water relations, salt balance, and nitrate leaching losses of a 960-acre citrus watershed. Soil Sci. 112:410-418.

6. Bolton, E.F., J.W. Aylesworth, and F.R. Hore. 1970. Nutrient losses through tile drains under three cropping systems and two fertility levels on a Brookston clay soil. Can. J. Soil Sci. 50:275-279.

7. Brasfield, J.F., V.W. Carlisle, and R.W. Johnson. 1973. Spodosols soils with a spodic horizon. Pages 57-60 of Soils of the *Southern States and Puerto Rico*, Bulletin No. 174, Agricultural Experiment Stations of the Southern States and Puerto Rico and the Soil Conservation Service of the United States Department of Agriculture.

8. Calvert, D.V. 1975. Nitrate, phosphate and potassium movement into drainage lines under three soil management systems. J. Envir. Qual. 4:183-186.

9. Calvert, D.V. and H.T. Phung. 1971. Nitrate-nitrogen movement into drainage lines under different soil management systems. Soil and Crop Sci. Soc. of Florida Proc. 31:229-232.

10. Calvert, D.V., J.G.A. Fiskell, R.S. Mansell, J.S. Rogers, L.C. Hammond, L.H. Allen, D.A. Graetz, E.H. Stewart, and W.M. Castle. 1976. Water and Soil Management For Citrus Production On Poorly-Drained Soils. Project Statement No. 01778, Florida Agricultural Experiment Stations, University of Florida, Gainesville.

(References Con't.)

11. Erickson, A.E. and B.G. Ellis. 1971. The nutrient content of drainage water from agricultural land. Research Bulletin No. 31, Agricultural Experiment Station, Michigan State University, East Lansing, Michigan.

12. Fausey, N.R. 1975. Numerical Model Analysis and Field Study of Shallow Subsurface Drainage. Ph.D. Dissertation, Department of Agronomy, Ohio State University, Columbus.

13. Fiskell, J.G.A. 1971. The effects of deep mixing and liming on cation selectivities of a Spodosol. Soil and Crop Sci. Soc. of Florida Proc. 31:223-228.

14. Fiskell, J.G.A. and D.V. Calvert. 1975. Effects of deep tillage, lime incorporation, and drainage on chemical properties of Spodosol profiles. Soil Sci. 120:132-139.

15. Fiskell, J.G.A. and R.S. Mansell. 1975. Dependence of P sorption in a Spodosol upon P rate, contact time, and deep tillage. Soil and Crop Sci. Soc. of Florida Proc. 34:34-38.

16. Fiskell, J.G.A., E.H. Stewart, and D.V. Calvert. 1970. Control of mobility of soil organic matter after trenching. Soil and Crop Sci. Soc. of Florida Proc. 30:122-130.

17. Frink, C.R. 1971. Plant nutrients and water quality. Agricultural Science Review (2nd quarter), pages 11-25.

18. Forbes, R.B., C.C. Hortenstine, and E.W. Bistline. 1974. Nitrogen, phosphorus, potassium and soluble salts in solution in a Blanton fine sand. Soil Crop Sci. Soc. Fla. Pro. 33:202-205.

19. Graetz, D.A., L.C. Hammond and J.M. Davidson. 1974. Nitrate movement in a Eustis fine sand planted to millet. Soil Crop Sci. Soc. Fla. Pro. 33:157-160.

20. Hamaker, J.W. 1972. Decomposition: quantitative aspects. Pages 253-340 of Organic Chemicals in the Soil Environment, Vol. 1, edited by C.A.J. Goring and J.W. Hamaker, Marcel Dekker, Inc., New York, N.Y.

21. Hammond, L.C., V.W. Carlisle, and J.S. Rogers. 1971. Physical and mineralogical characteristics of soils in the SWAP experimental site at Fort Pierce, Florida. Soil and Crop Sci. Soc. of Florida Proc. 31:210-214.

22. Hague, R. and V.H. Freed. 1974. Behavior of pesticides in the environment: "Environmental chemodynamics". Residue Reviews 52:89-116 (see page 108).

23. Hassall, K. 1969. World Crop Protection 2. Pesticides. Chemical Rubber Company, Cleveland, Ohio.

(References Con't.)

24. Johnson, W.R., F. Ittihadieh, R.M. Daum, and A.F. Pillsbury. 1965. Nitrogen and phosphorus in tile drainage effluent. Soil Sci. Soc. Amer. Proc. 29:287-289.

25. Jolliffee, V.A., B.E. Day, L.S. Jordon, and J.D. Mann. 1967. Method of determining bromacil in soils and plant tissue. J. Agr. Food Chem. 15:174-177.

26. Jury, W.A. 1975. Solute travel-time estimates for tile-drained fields. I. Theory. Soil Sci. Soc. Amer. Proc. 39:1020-1024.

27. Kaddah, M.F. 1976. Deep tillage enhances crop growth in a stratified sandy soil. Paper No. 75-1556 presented at the 1975 Winter Meeting of the American Society of Agricultural Engineers, Chicago, Illinois.

28. Kirkham, Don, Sadik Toksoz, and R.R. Van Der Ploeg. 1974. Steady flow to drains and wells. Pages 203-244 of Drainage For Agriculture, Monograph No. 17, American Society of Agronomy, edited by Jan Van Schilfgaarde, Madison Wisconsin.

29. Knipling, E.B. and L.C. Hammond. 1971. The SWAP study of soil water management for citrus on flatwood soils in Florida. Soil and Crop Sci. Soc. of Florida Proc. 31:208-210.

30. Mansell, R.S., W.B. Wheeler, Lita Elliott, and Mark Shaurette. 1971. Movement of Acarol and Terbacil pesticides during displacement through columns of Wabasso fine sand. Soil and Crop Sci. Soc. of Florida Proc. 31:239-243.

31. Mansell, R.S., H.M. Selim, and J.G.A. Fiskell. 1977. Simulated transformations and transport of phosphorus in soil. Soil Sci. (in press).

32. Mansell, R.S., H.M. Selim, P. Kanchanasut, J.M. Davidson, and J.G.A. Fiskell. 1977. Experimental and simulated transport of phosphorus through sandy soils. Water Resources Research 13:189-194.

33. Nelson, L.B. 1972. Agricultural chemicals in relation to environmental quality: chemical fertilizers, present and future. J. Envir. Qual. 1:1-6.

34. Nelson, L.B. 1975. Fertilizers for all-out food production. Pages 15-28 in All-Out Food Production: Strategy and Resource Implications. Special Publication No. 23, American Society of Agronomy, Madison, Wisconsin.

35. Pease, H.L. 1966. Determination of bromacil residues. J. Agr. Food Chem. 14:94-96.

36. Phung, H.T. 1971. Dissolved oxygen in tile-drain outflow water-measurement and affecting factors. Soil and crop Sci. Soc. of Florida Proc. 31:233-237.

(references con't.)

37. Phung, H.T. 1972. Reduction processes in modified Spodosol systems and their effect on some plant responses. Ph.D. Dissertation, University of Florida, Gainesville, 209 p.

38. Ponnamperuma, F.N. 1972. The chemistry of submerged soils. Advances in Agronomy 24:29-90.

39. Powell, N.L. and Don Kirkham. 1974. Flow patterns of rain water through sloping soil surface layers and the movement of nutrients by runoff. Completion Report No. ISWRRI-64, Iowa State Water Resources Research Institute, Iowa State University, Ames, Iowa.

40. Reitz, Herman J. 1961. Why citrus needs nutrition. Better Crops With Plant Food Magazine, American Potash Institute, Washington, D.C.

41. Rogers, J.S. and E.H. Stewart. 1974. Hydraulic gradients near drains in modified soil profiles. Soil and Crop Sci. Soc. of Florida. 33:148-150.

42. Rogers, J.S., C.L. Simmons, and L.C. Hammond. 1971. Drainage characteristics of Oldsmar sand simulated on a resistance network. Soil and Crop Sci. Soc. of Florida Proc. 31:218-220.

43. Selim, H.M., P. Kanchanasut, R.S. Mansell, L.W. Zelazny, and J.M. Davidson. 1975. Phosphorus and chloride movement in a Spodosol. Soil and Crop Sci. Soc. of Florida Proc. 34:18-23.

44. Sites, J.W., L.C. Hammond, R.A. Leighty, W.O. Johnson, and K.D. Butson. 1964. Information to Consider in the Use of Soils of Flatwoods and Marshes for Citrus. Circular S-135-A, University of Florida, Agricultural Experiment Stations, Gainesville.

45. Stanford, G., R.A. Vander Pol, and S. Dzienia. 1975. Denitrification rates in relation to total and extractable soil carbon. Soil Sci. Soc. Amer. Proc. 39:284-289.

46. Stewart, E.H. and R.R. Alberts. 1971. Rate of subsurface drainage as influenced by groundwater levels in modified profiles of Florida flatwood soils. Soil and Crop Sci. Soc. of Florida Proc. 31:214-215.

47. Talsma, T. 1967. Leaching of tile-drained saline soils. Aus. J. Soil Res. 5:37-46.

48. Van Schilfgaarde, Jan. 1974. Nonsteady flow to drains. Pages 245-270 of Drainage for Agriculture, Monograph No. 17. American Society of Agronomy, edited by Jan Van Schilfgaarde, Madison Wisconsin.

49. Wesseling J. 1973. Subusrface flow into drains. Pages 1-58 of Drainage Principles and Application II. Theories of Field Drainage and Watershed Runoff, Publication 16 (vol. II), International Institute for Land Reclamation and Improvement. Wageningen, The Netherlands.

(Reference con't.)

50. Wheeler, W.B., H.A. Moye, C.H. Van Middlelem, N.P. Thompson, and W.B. Tappan. 1969. Residues of endrin and DDT in turnips grown in soil containing these compounds. Pest. Mont. J. 3:72-76.

51. Wheeler, W.B., D.F. Rothwell, and D.H. Hubbell. 1973. Persistence and microbiological effects of Acarol and Chlorobenzilate in two Florida soils. J. Environ. Qual. 2:115-118.

52. Wheeler, W.B., N.P. Thompson, B.R. Ray, and Merrill Wilcox. 1971. Analysis of terbacil by electron capture gas chromatography. Weed Science 19:307.

53. Zelazny, L.W. and V.W. Carlisle. 1971. Mineralogy of Florida Aeric Haplaquods. Soil and Crop Sci. Soc. Florida Proc. 31:161-165.

Appendix: TITLES AND ABSTRACTS FOR PUBLISHED PAPERS RESULTING FROM THIS RESEARCH

(1) Selim, H.M., P. Kanchanasut, R.S. Mansell, L.W. Zelazny, and J.M. Davidson. 1975. Phsophorus and chloride movement in a Spodosol. Soil and Crop Sci. Soc. of Florida Proc. 34:18-23.

Phosphate (P) and chloride (Cl) movement was determined in an Oldsmar fine sand using miscible displacement techniques for undistrubed cores from A_1, A_2, and B_{2h} horizons. Cl mobility exceeded that of P in the A_1 and B_{2h} soils. In the A_2 soil, the shape of the breakthrough curves for P and Cl were similar. Phosphorus adsorption caused much higher retardation in P movement in the highly sorptive A_1 and B_{2h} soils than in the A_2 soil. Asymmetry and excessive tailing of P breakthrough curves for the A_1 and B_{2h} soils suggest nonsingular as well as nonequilibrium adsorption of phosphorus. These soils showed nonlinear adsorption isotherms. Decreasing the pore water velocity in B_{2h} resulted in less elution of applied P but the effect of pore velocity had negligible effects upon P breakthrough curves for A_2. For the A_1 soil, less P was eluted from water-unsaturated than saturated soil. Calculated results did not adequately describe P movement; however, good agreement was obtained for Cl movement in all soils.

(2) Fiskell, J.G.A. and R.S. Mansell. 1975. Dependence of P sorption in a Spodosol upon P rate, contact time, and deep tillage. Soil and Crop Sci. Soc. of Florida Proc. 34:34-38.

Hectare-size plots of Oldsmar fine sand (Alfic arenic haplaquod) were previously surface tilled (ST), deep tilled unlimed to 105 cm (DT), or deep tilled with dolomite incorporation (DTL) prior to tile drainage. Samples were taken at 10 depths in 15-cm intervals. The samples were sieved and subjected to phosphate applications from 1 to 480 μg P/g soil in 0.01 M $CaCl_2$. Langmuir adsorption isotherms were made on four depths from each soil modification and also P sorption was studied at 200 ppm P/g soil level for periods of 3 minutes, 10 minutes, 2 hours, 1 day, and 14 days. In the ST soil, 7, 87, and 89% of 200 ppm P were retained after 24 hours by the A, B_h, and B_{22} horizons, respectively; in DT and DTL soils at corresponding depths, P sorption ranged from 64 to 91%. Most of the P sorption was attributed to spodic soil. With B_{22} soil, P sorption was linearly proportional on a semi-log scale to contact time; however, with B_h soil and both DT and DTL (0-105 cm) soil, P sorption was not linear with increase in contact time. Phosphate loss to drainage was probable in ST soil because of low P retention in the A horizon and very low permeability of the B_h and B_{22} horizons; in DT and DTL, incorporation of the latter horizons provided good P sorption in the depths.

(3) Mansell, R.S., H.M. Selim, P. Kanchanasut, J.M. Davidson, and J.G.A. Fiskell. 1977. Experimental and simulated transport of phosphorus through sandy soils. Water Resources Research (in press).

Reversible equilibrium adsorption-desorption relationships were inadequate for describing the transport of orthophosphate through water-saturated and unsaturated cores from surface (A_1) and subsurface (A_2) horizons of Oldsmar fine sand. Using a kinetic model with nonlinear reversible adsorption-desorption improved descriptions of phosphorus transport through these soils. Phosphorus effluent concentrations were described best using an irreversible sink for chemical immobilization or precipitation with a nonlinear reversible, kinetic adsorption-desorption equation.

(4) Mansell, R.S., H.M. Selim, and J.G.A. Fiskell. 1977. Simulated transformations and transport of phosphorus in soil. Soil Sci. (in press).

A mechanistic, multistep model was developed using chemical kinetics and mass transport theory to describe transformations and movement of orthophosphate in soil. Soil phosphorus was assumed to occur simultaneously in any of four primary phases: water-soluble, physically adsorbed, immobilized (or chemisorbed), and precipitated. The kinetics of reactions which control the transformation of phosphorus between any two of the four phases were considered to be reversible and of N^{th} order. A range of values for the reaction rate coefficients were used in the model to describe the transport of applied phosphorus in the solution phase during steady water flow through a soil initially devoid of phosphorus.

(5) Kanchanasut, Pimpan. 1974. Influence of soil water content and flow velocity upon miscible displacement of phosphate and chloride in undisturbed cores of a Spodosol. M. Sci. Thesis, Soil Science Department, University of Florida, Gainesville.

Excessive tailing of the desorption slope of the P breakthrough curves indicated that desorption process was very slow at low concentration of P for soil cores from A_1 and B_{2h} horizons. In water-unsaturated conditions, the breakthrough curves showed that P was less mobile than for saturtions, the breakthrough curves showed that P was less mobile than for saturated conditions.

The behavior of P movement in undisturbed soil cores was investigated using miscible desplacement techniques. Undistrubed cores of 5.4 cm diameter and 10 cm length were collected from the A_1, A_2, and B_{2h} horizons of noncultivated Oldsmar fine sand. Three flow rates were used in studies of watersaturated flow through the A_1 and A_2 horizons. Unsaturated flow was maintained with 15 and 30 cm soil water pressure in cores of A_1 and A_2 horizons located in a specially designed air pressure chamber. Aqueous solutions of 100 ppm P as $Ca(H_2PO_4)_2$ were displaced through aqueous 0.01 N $CaSO_4$ saturated cores obtained from the A_1 and A_2 horizons and 1000 ppm P was passed through cores obtained from the B_{2h} horizon. Chloride-36 was used as a tracer of water movement in the soil.

Analyses of the breakthrough curves indicated that rates of P movement in Oldsmar fine sand were in the order of $A_2 > A_1 > B_{2h}$ horizon. The movement of P in the A_2 horizon was similar to that for $^{36}Cl^-$ indicating that P was not retained by the soil.